Design Status of the LBNF/DUNE Beamline

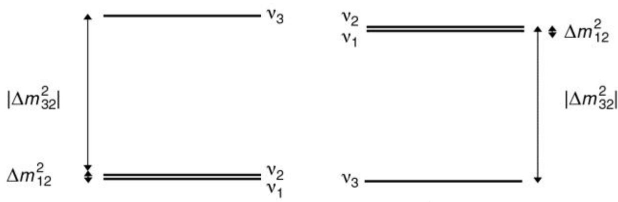
Vaia Papadimitriou
LBNF Beamline Manager
Accelerator Division Headquarters – Fermilab

Accelerator Physics and Technology Seminar
Fermilab, November 28, 2017

Outline

- LBNF/DUNE Science Goals
- Scope of LBNF and DUNE
- The Near Site Facility
- Main Requirements & Assumptions
- Beamline Design Overview
- Recent changes
- Challenges and R&D issues
- Beamline Project Team and International Partners
- Cost, milestones and plan forward
- Summary and Conclusion

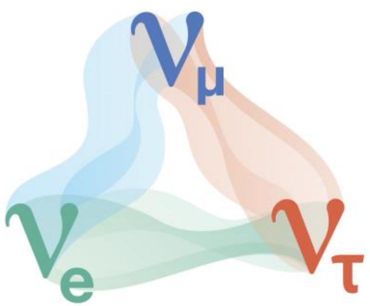
LBNF/DUNE Science Goals



In a single experiment

LBNF/DUNE is a comprehensive program to:

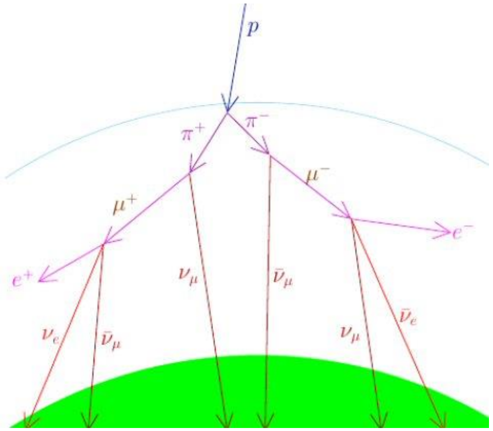
- Measure neutrino oscillations
  - Direct determination of CP violation in the leptonic sector
  - Measurement of the CP phase δ
  - Determination of the neutrino mass hierarchy
  - Determination of the θ_{23} octant and other precision measurements
  - Testing the 3-flavor mixing paradigm
  - Precision measurements of neutrino interactions with matter
  - Searching for new physics



LBNF/DUNE Science Goals

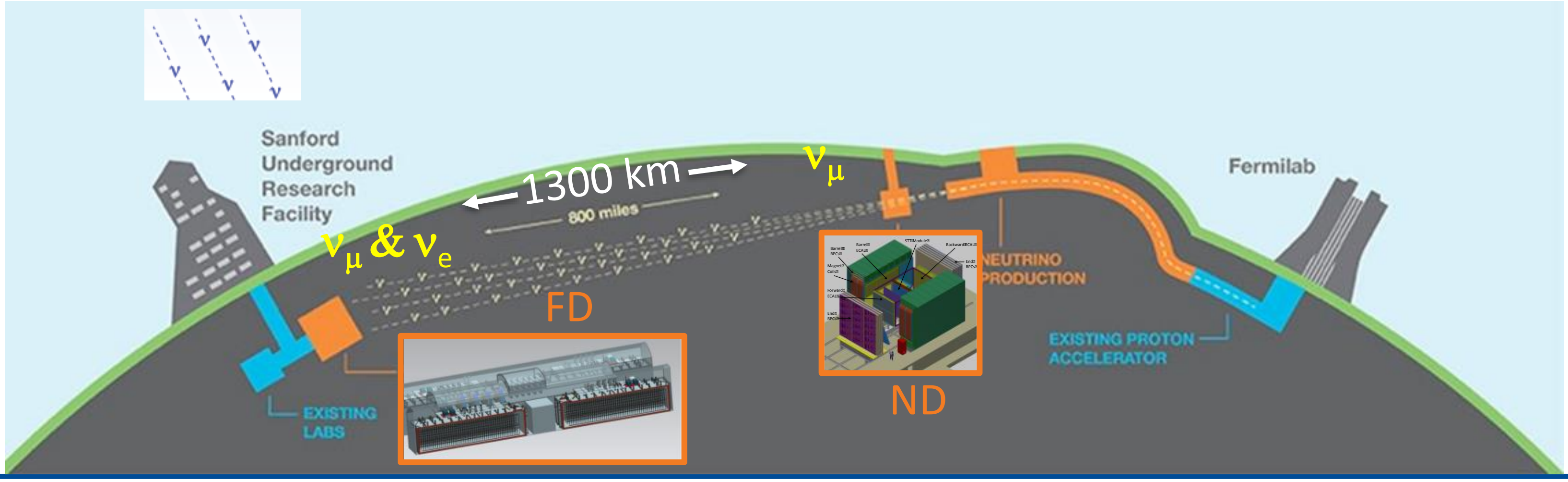
LBNF/DUNE is a comprehensive program to:

- 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



Facility and Experiment

- **LBNF (Long Baseline Neutrino Facility)**:
  - Near site: Fermilab, Batavia, IL – facilities and infrastructure to:
    - create a broad band 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 (Deep Underground Neutrino Experiment)**:
  - Near site detectors (LAr-TPC and a multipurpose tracking detector) and Far site detectors (four 10-kt LAr-TPC modules)



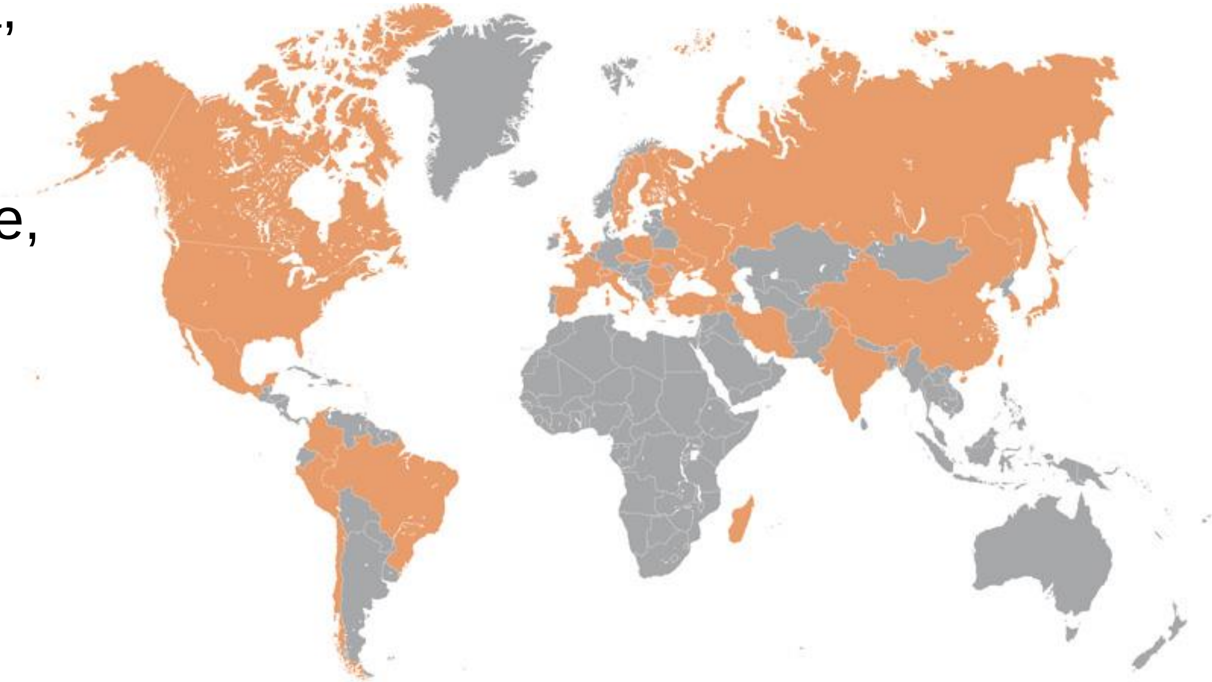
DUNE Collaboration

> 50% non-US

As of today:

1120 collaborators from 175 institutions in 31 nations

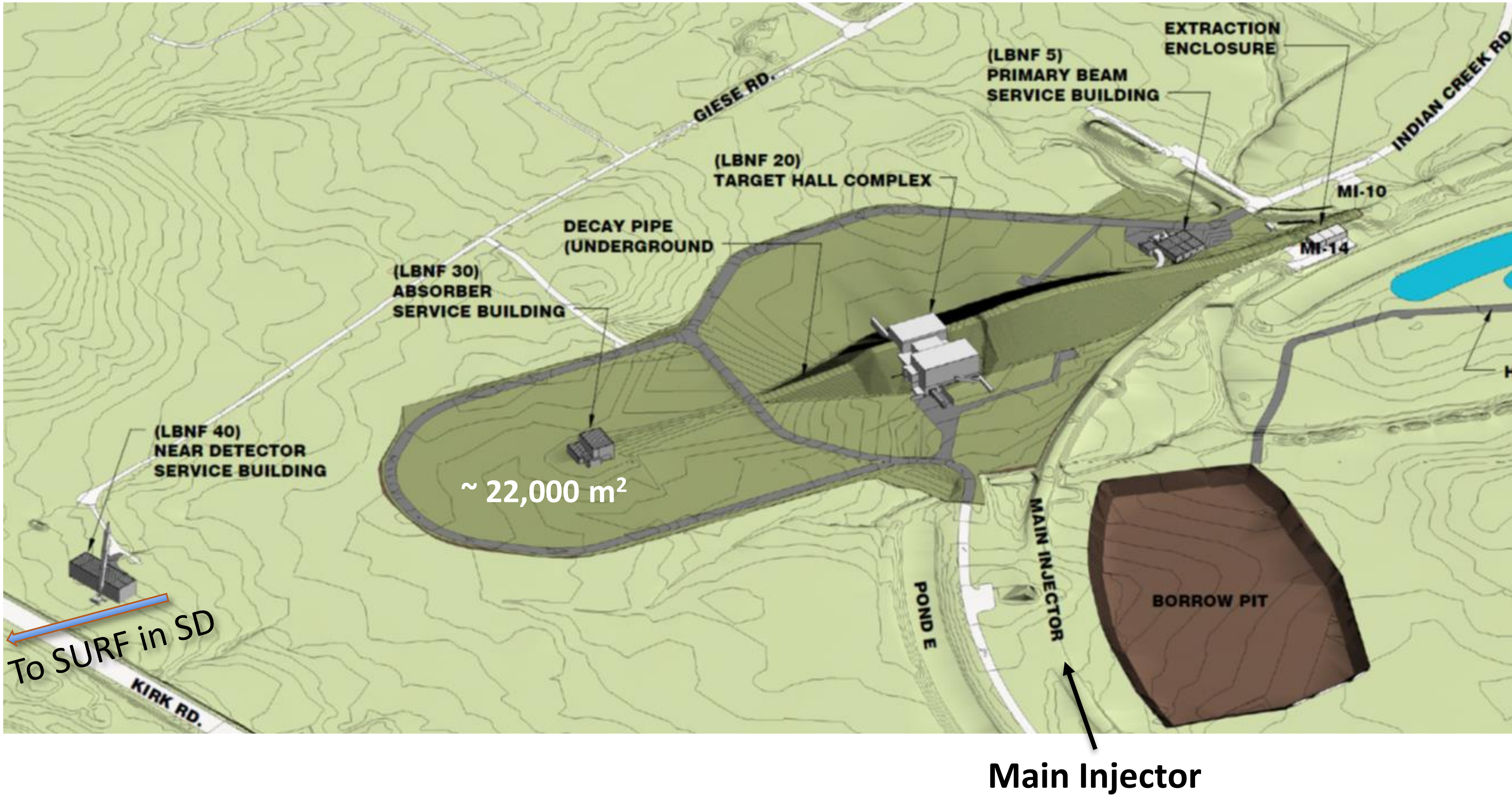
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA



DUNE Collaboration

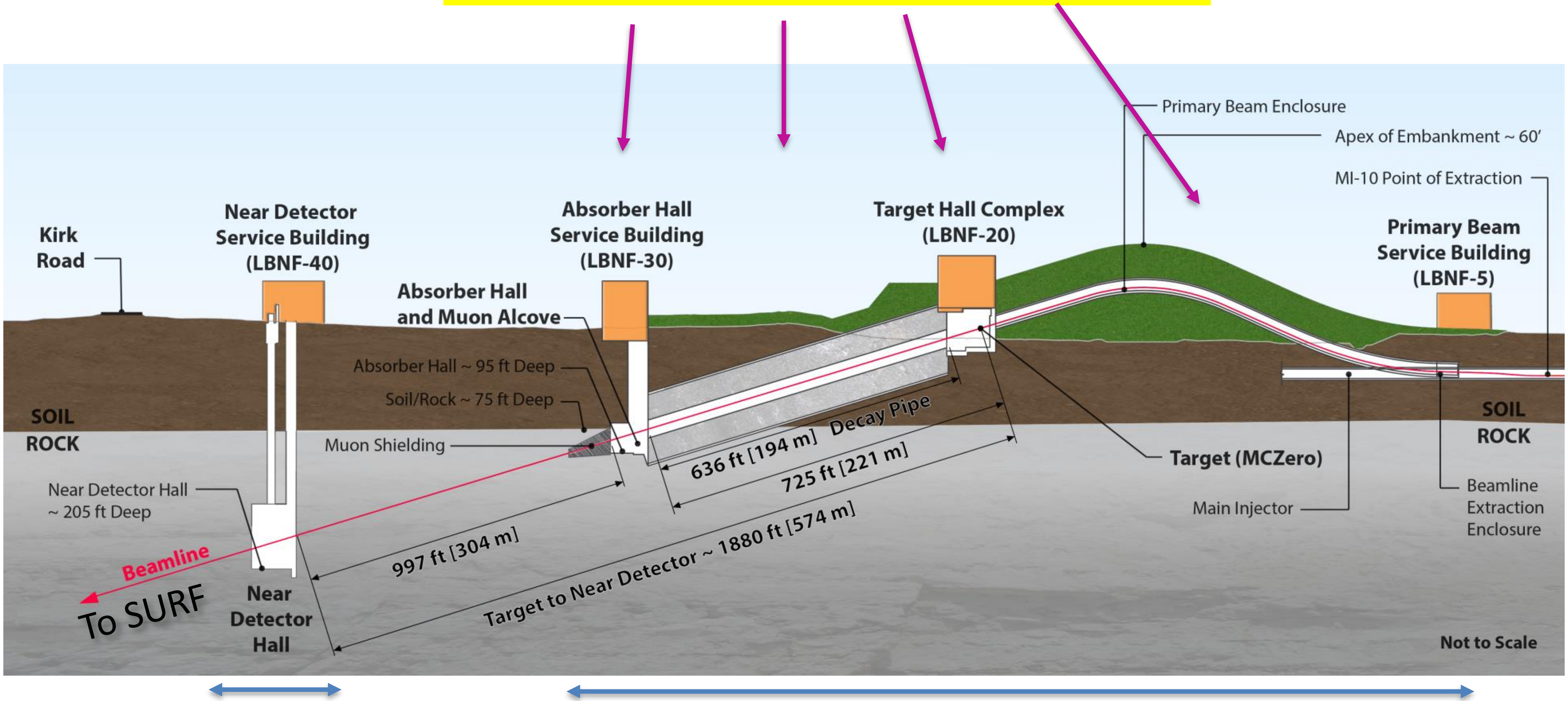
Layout of the LBNF Fermilab Facility

Proton beam extracted from the MI-10 section of the Main Injector



Longitudinal Cross Section of the LBNF Beamline

Scope for Beamline Technical Components



Tunneled excavation

Constructed in Open Cut

Strong Interface and close collaboration with the Near Site Conventional Facilities Team

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
- Conventional Facilities for the Beamline (separate L3 WBS).

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.
- 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, CD-4 expected in Spring 2027).
- Facility is upgradeable to 2.4 MW proton beam power (PIP-III).

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.
- LBNF provides a 6-cell storage morgue (2 components/cell) with sufficient space for 2 years of LBNF running at 1.2 MW (OK for 2.4 MW). Expect to use the C-0 Remote Handling Facility for longer term storage of some of the LBNF components.

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 ≤1.2 MW and ≤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)x10^{21} POT/yr

Pulse duration: 10 μs

Beam size at target: tunable 1.0-4.0 mm

Brief History

- CD-1 approval in December, 2012 (LBNE).
- Fully International Collaboration formed in January, 2015. It evolved to LBNF/DUNE by March, 2015.
- CD-1R (Refresh) approval in November, 2015 (LBNF/DUNE).
- CD-3a approval in September, 2016 (Far Site pre-excavation and excavation – South Dakota).
  - Groundbreaking for the Far Site: July 21, 2017.
  - Far-site CMGC (Construction Manager General Contractor) awarded on Aug. 8, 2017. Far-site final design launched officially on Nov. 8, 2017.
- DUNE prototype detectors are under construction at CERN.
- A three-year long Beam optimization effort to improve the physics potential of DUNE was concluded successfully with a conceptual design and cost/schedule review on Oct. 5-6, 2017.
- LBNF/DUNE decision to implement the optimized beamline design, Nov. 2, 2017.

LBNF/DUNE Scope and Milestones

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

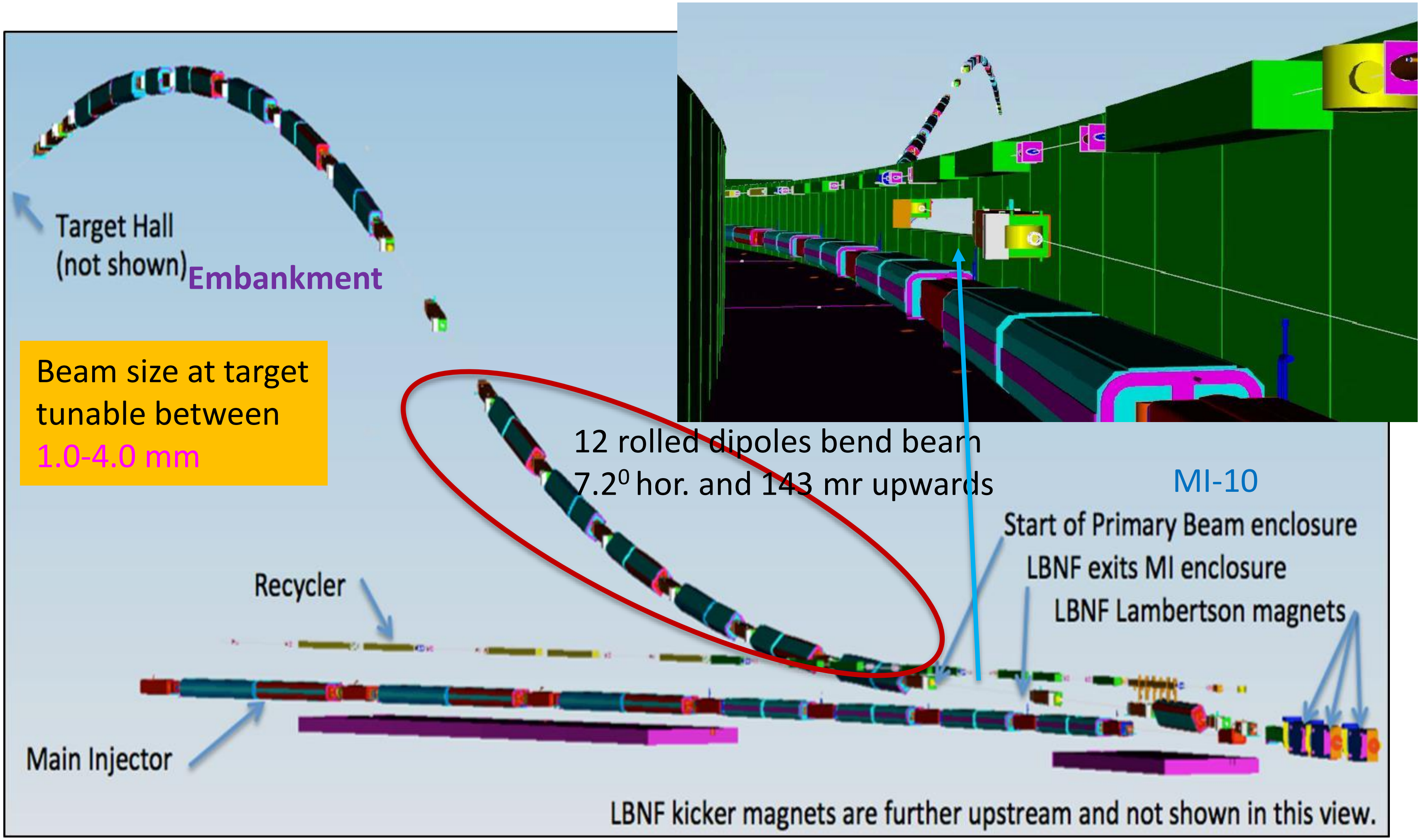
- Contract awarded for LBNF preconstruction services: August 9, 2017. Kick-off meeting on August 29, 2017.

Beamline Design Overview

(Optimized Neutrino Beamline)

Primary Beamline

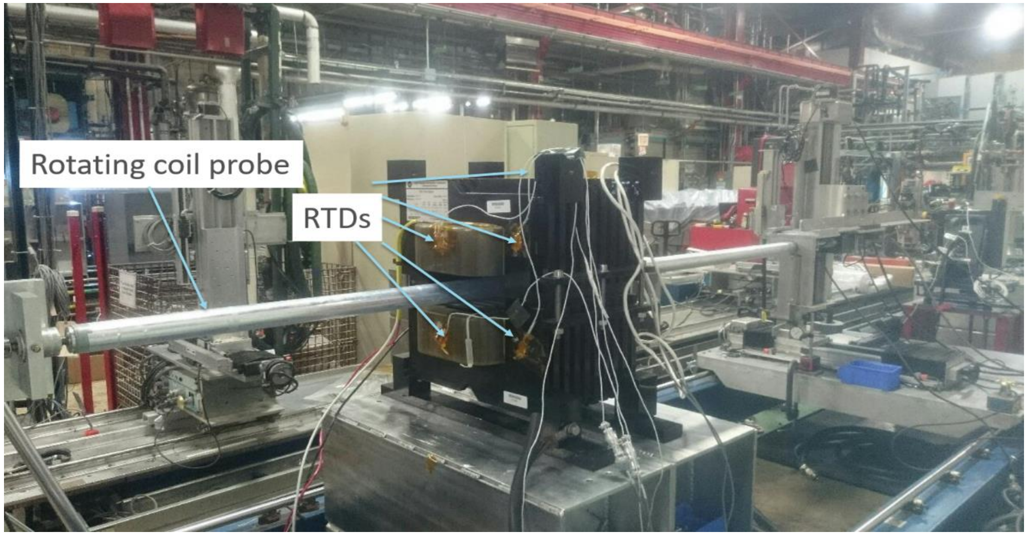
Beam optics point to 79 conventional magnets: 25 dipoles, 21 quadrupoles, 23 correctors, 6 kickers, 3 Lambertsons, 1 C Magnet

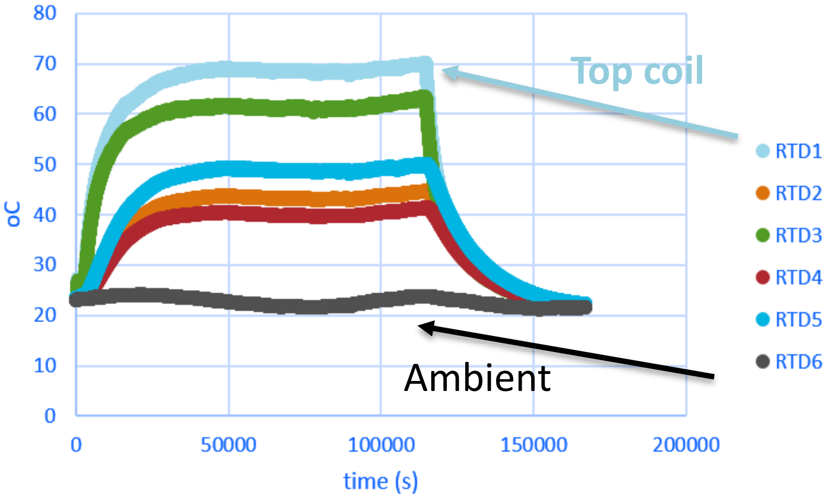


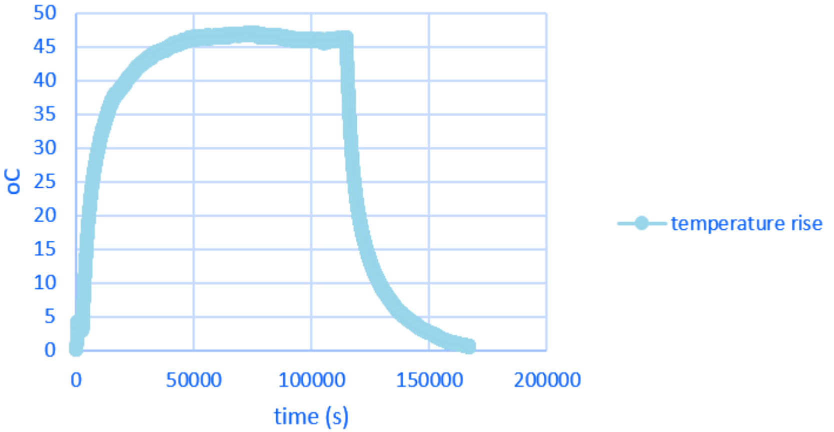
LBNF prototype corrector magnet testing

- Corrector magnet prototype (FNAL design, assembled at IHEP/China) has been tested at IHEP and Fermilab - thermal studies

Magnet on the test stand at Technical Division (aper. 5”x3”)



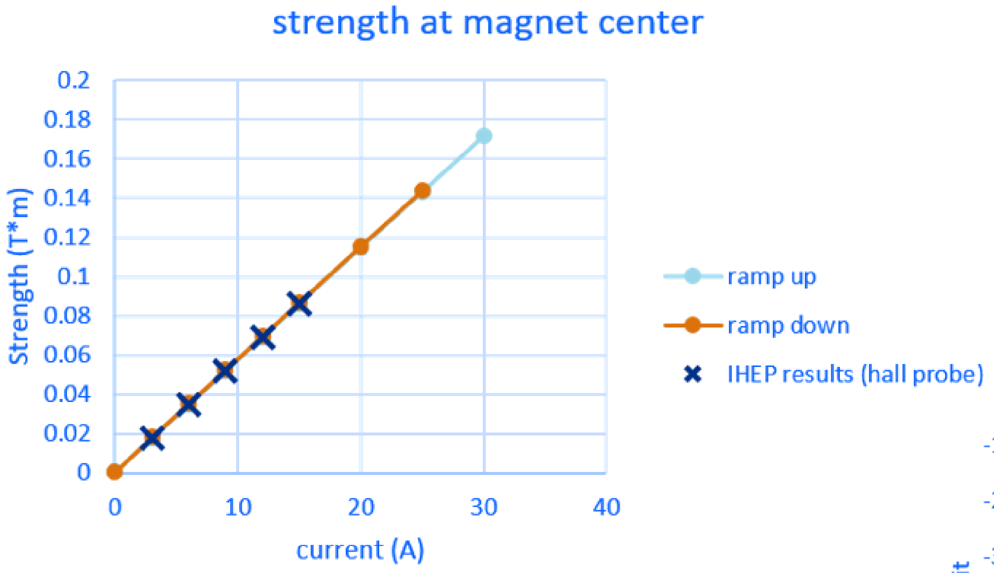




The magnet current maintained at 15 A till equilibrium (13-14 h) and then shut-down to allow the magnet to cool naturally.

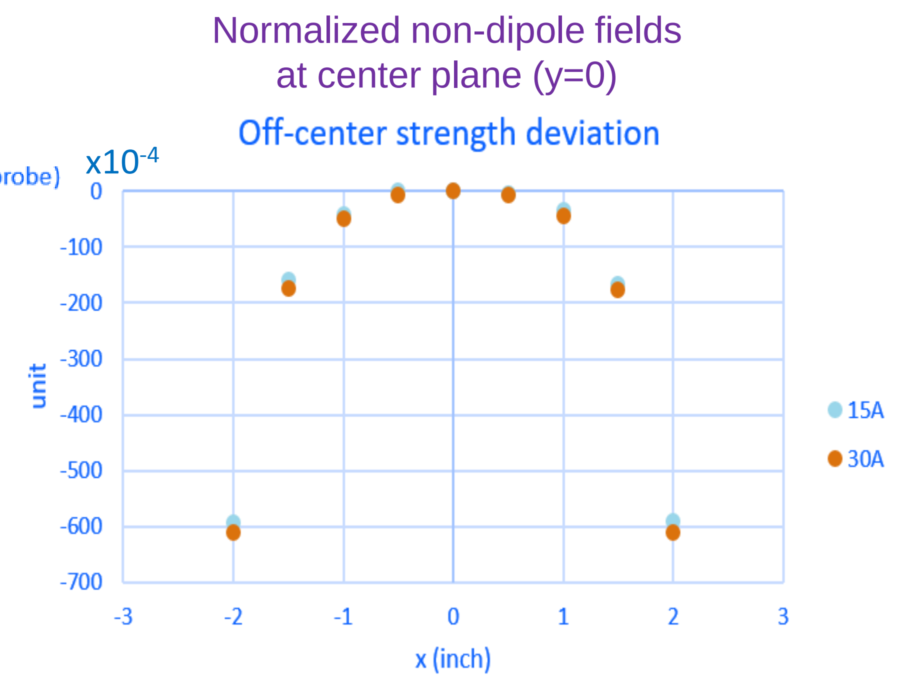
LBNF prototype corrector magnet testing

- Corrector magnet prototype has been tested at IHEP and Fermilab - magnetic measurements.



Linearity of field vs current is better than 4.5% at all currents

Field quality in central aperture (2”x2”) better than 0.75%

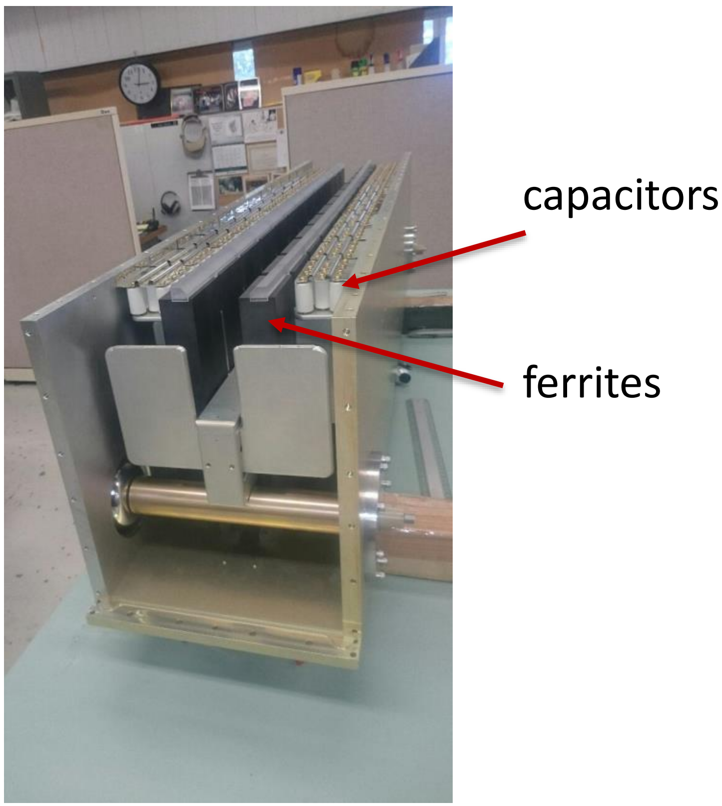


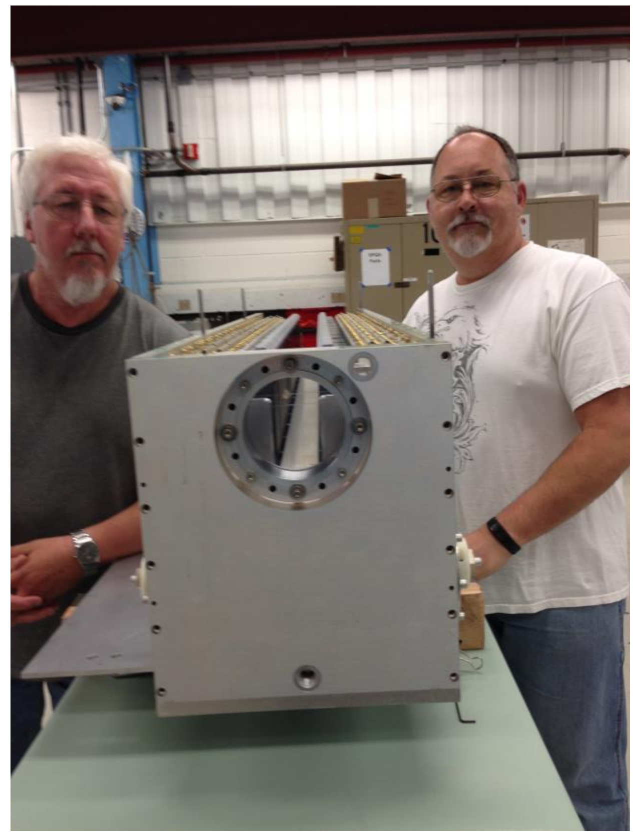
- Final Design Review for the corrector magnet, Dec 1, 2017 – Fermilab.
- Production readiness review in January 2018 - IHEP.

LBNF kicker prototype magnet

- Kicker prototype assembly complete at Fermilab by the end of May, 2017. Testing will follow at AD between December 2017 and March 2018.

Kicker magnet prototype





Producing a neutrino beam

proton

meson

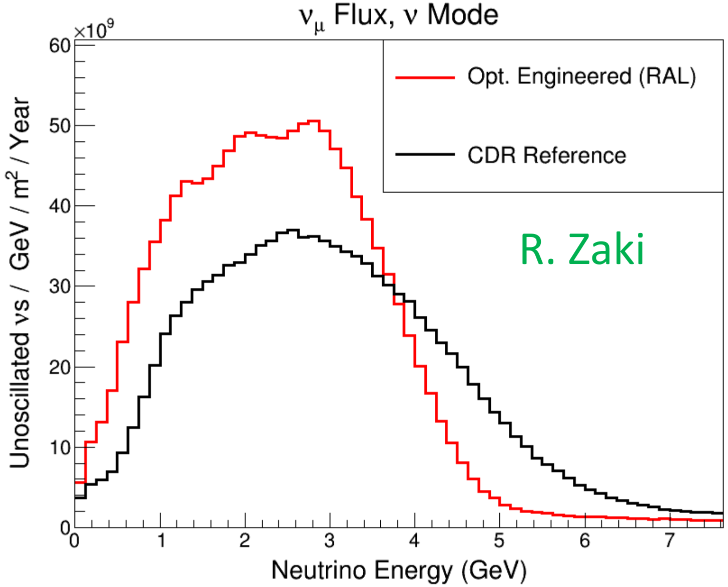
Artwork by Sandbox Studio

Optimizing target and horns

- Have been optimizing target and horns for better physics for the past three years, on the basis of sensitivity to CP violation.
- Encouragement by the CD-1R Review Committee (July 2015) to continue along these lines.

> Recommendation: Actively pursue further improvements to the target and horn layout with an overall goal of reducing the time to obtain first physics results.

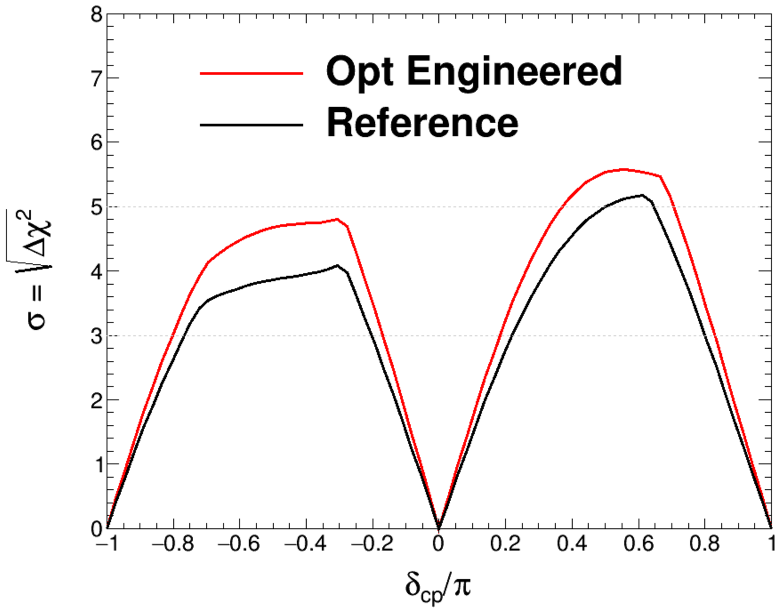
- The optimization leads to significantly more flux, a flatter spectrum in the energy range of interest and reduced high energy tail.

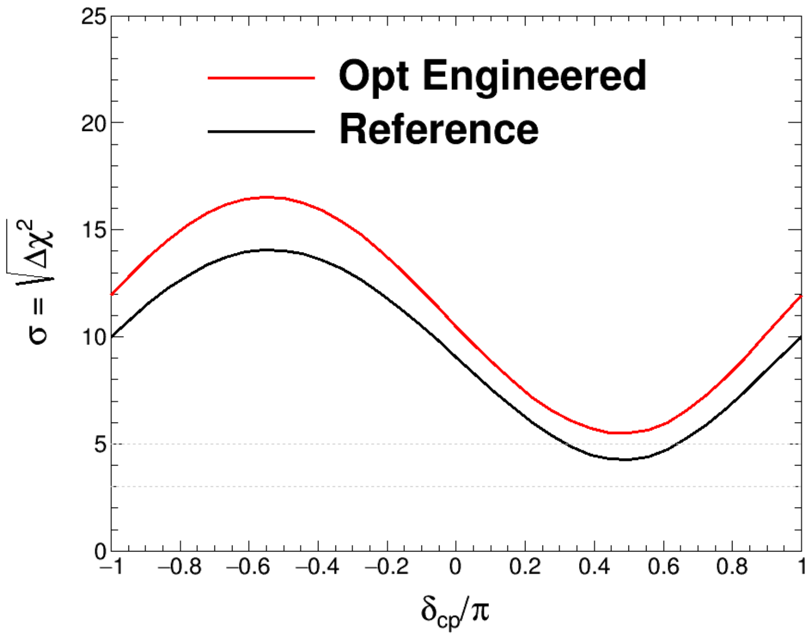


- The optimized design points to a four interaction length target (instead of 2λ) and to three horns of new design (instead of two NuMI-like horns).
- ~ 36% improvement in the flux within the 1-4 GeV region of neutrino energy.

Optimizing Target and Horns

- Improvements in physics sensitivities

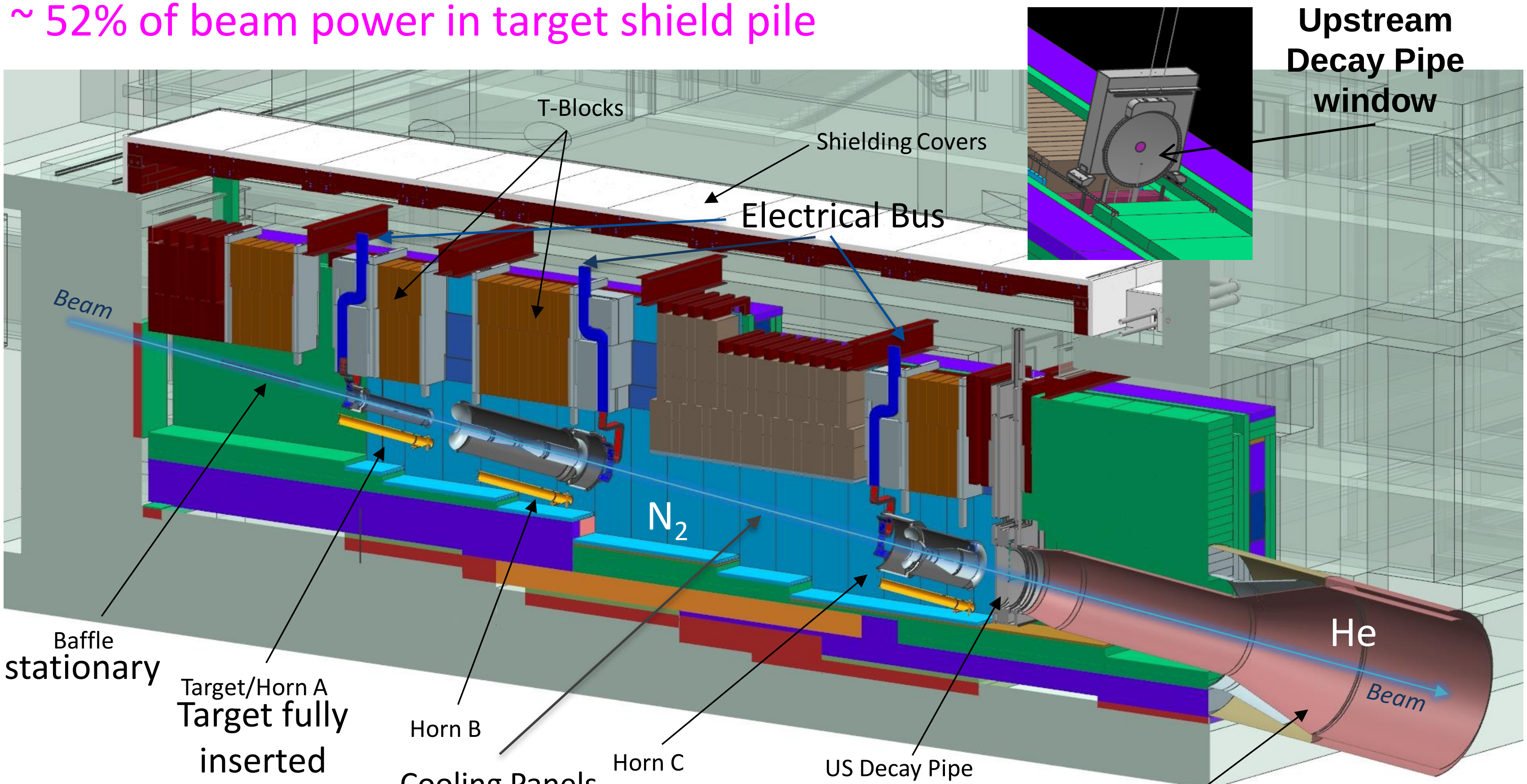




Sensitivities assume exposure of 300 kT MW years; CP sensitivity assumes a normal mass hierarchy

Target Shield Pile layout – longitudinal cross section

~ 52% of beam power in target shield pile



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 instead of nitrogen at CD-1R).

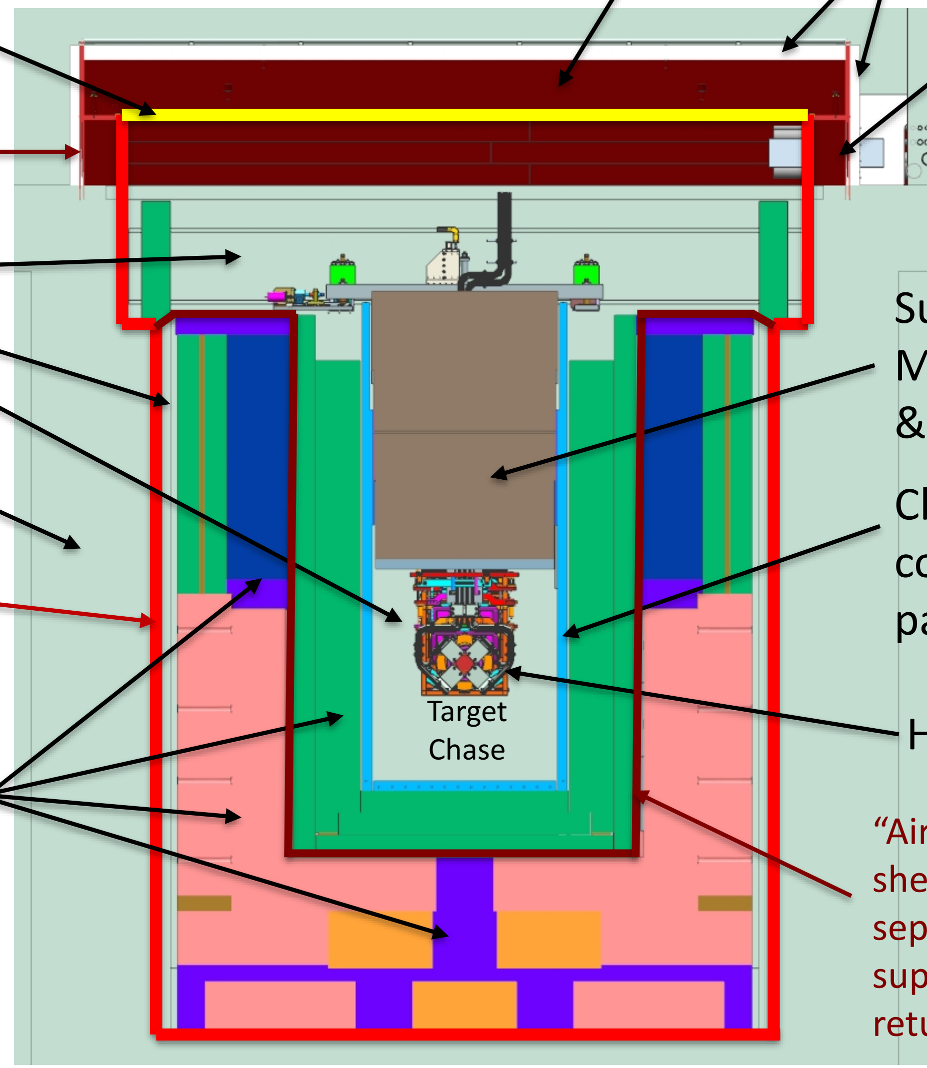
Target chase atmosphere and cooling of the decay pipe

- Nitrogen and helium were considered alternatives to air at CD-1R.
- Refined air-release calculations after CD-1R motivated the switch to nitrogen instead of air for the filling/cooling of the target chase and the cooling of the helium-filled decay pipe.
  - Reduced ^{41}Ar; better seals reduce the release of the short lived radionuclides ^{11}C and ^{13}N – max leak rate 7 cfm vs 266 cfm for air.
  - As a result, MEOI is 29.9% out of LBNF target hall complex and 22.5% if we use the primary beam area as well (aiming for no more than 30%)

- This was the subject of a dedicated and successful review in July, 2017.

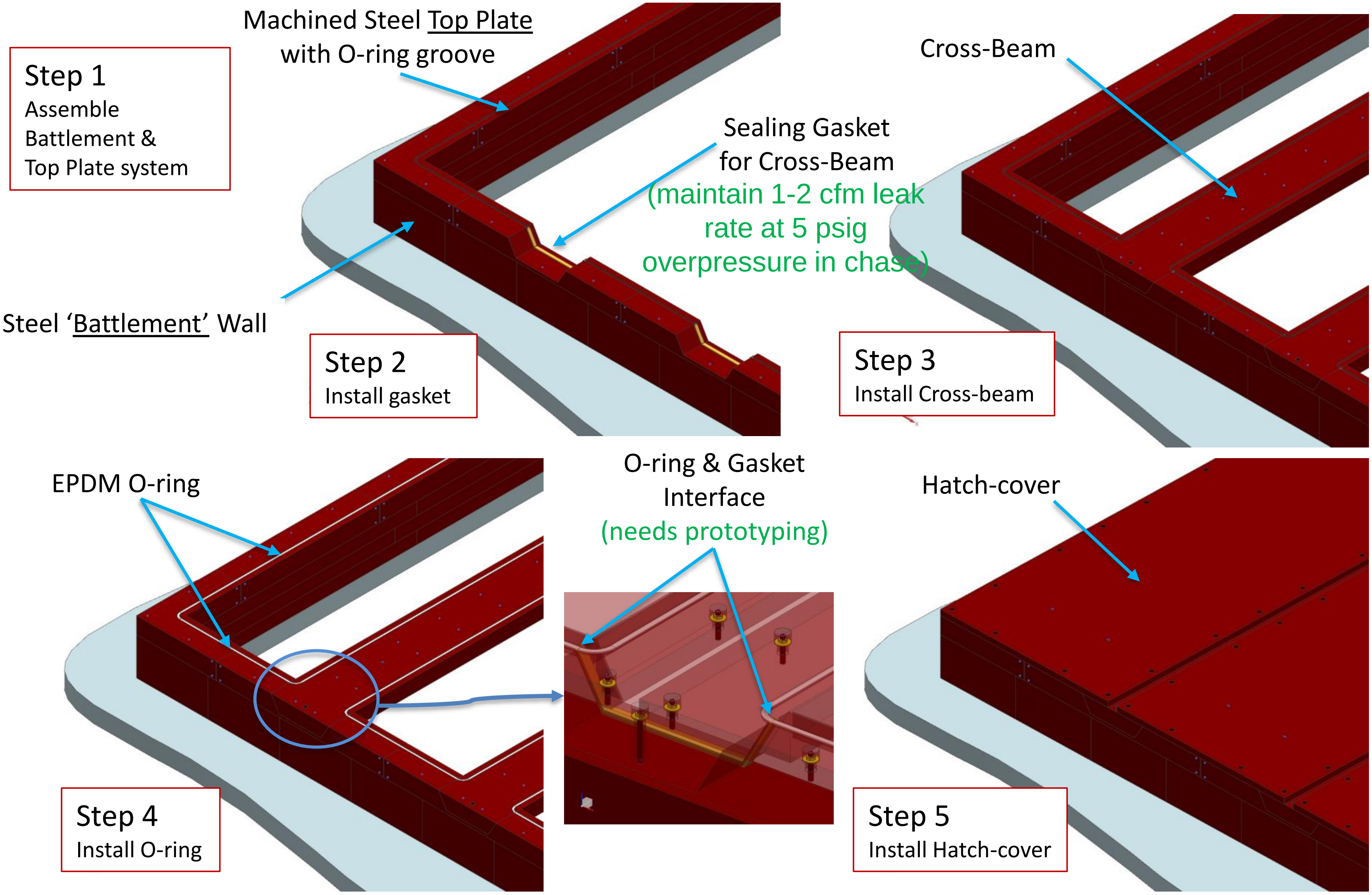
- Having nitrogen in the target chase instead of air addresses corrosion concerns as well. (Corrosion working group studies).

Target Station – Leak Tight Barrier System



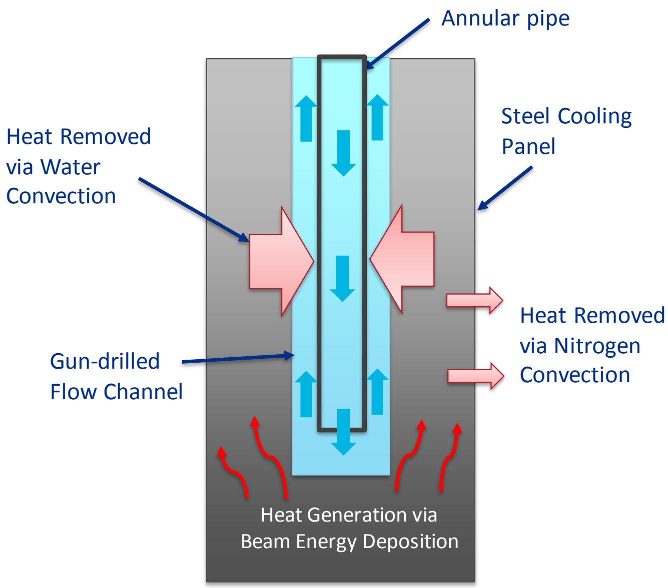
N_2 flows upstream through the top and side passages and returns downstream through the chase. Some N_2 flows through the gaps in T-blocks and bulk steel shielding.

Hatch Cover Seal Conceptual Design

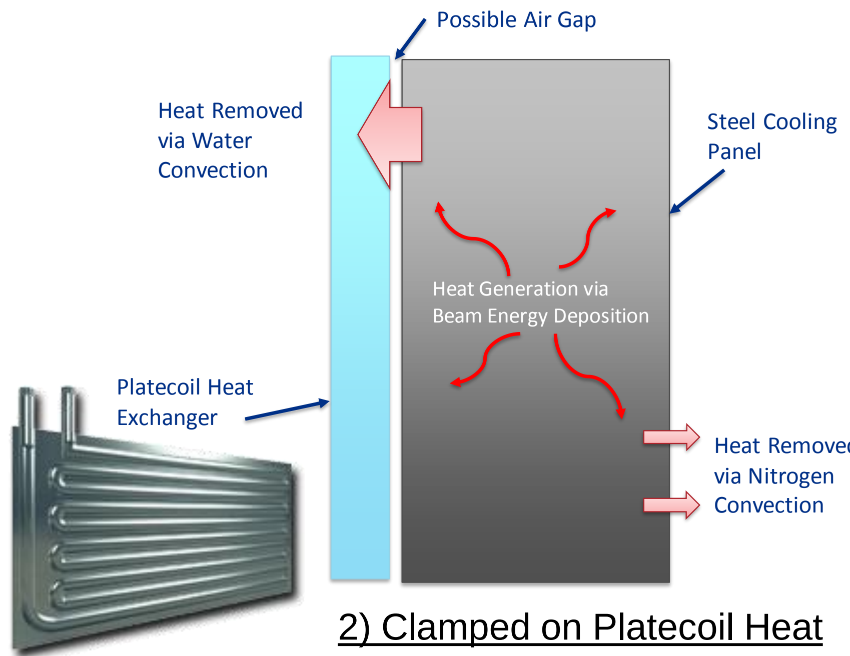


Target Shield Pile - Cooling Panel Design

- U-Shape Cooling Panels are 4 inch thick carbon steel. Panels are replaceable.
- Two cooling option being considered:
  - 1) Gun drilled water cooling channels – limitation on how deep one can gun drill.
  - 2) Clamped on commercially available Platecoil Heat Exchangers (stainless steel)
- Plan is to further investigate 2nd option – simpler and more cost effective. May also consider carbon steel/cast iron blocks with embedded stainless steel pipes.

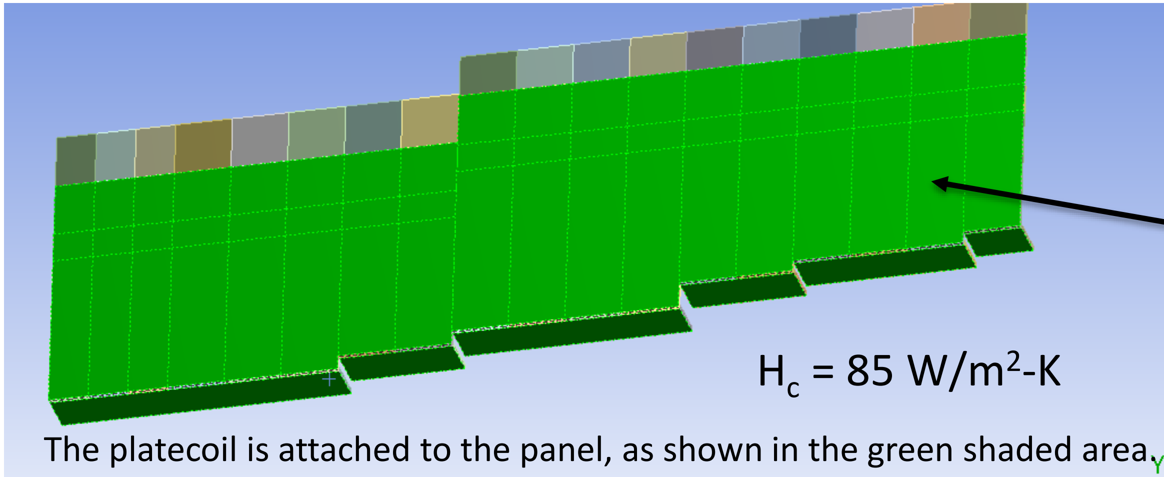


1) Gun-drilled Water Channels in the 4 inch Steel Cooling Panel



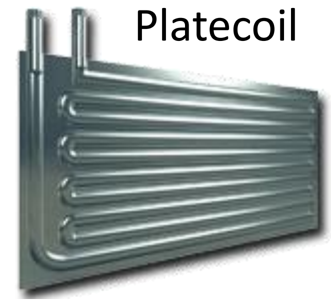
2) Clamped on Platecoil Heat Exchanger

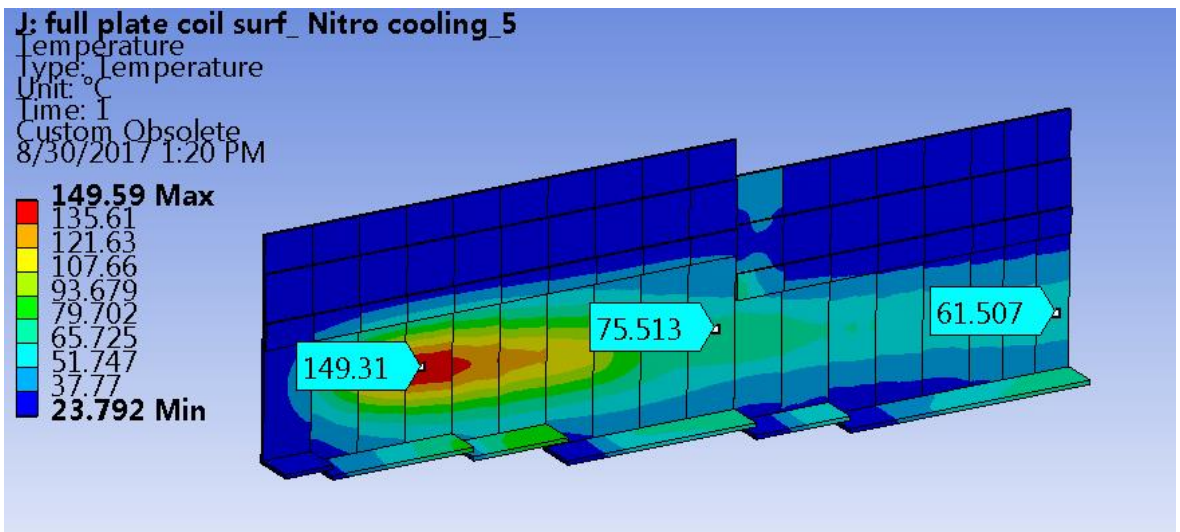
Cooling Panel Design – FEA at 2.4 MW Optimized Configuration



U shape panel half structure. 542 KW heat is deposited into the cooling panels.

Platecoil





Results:

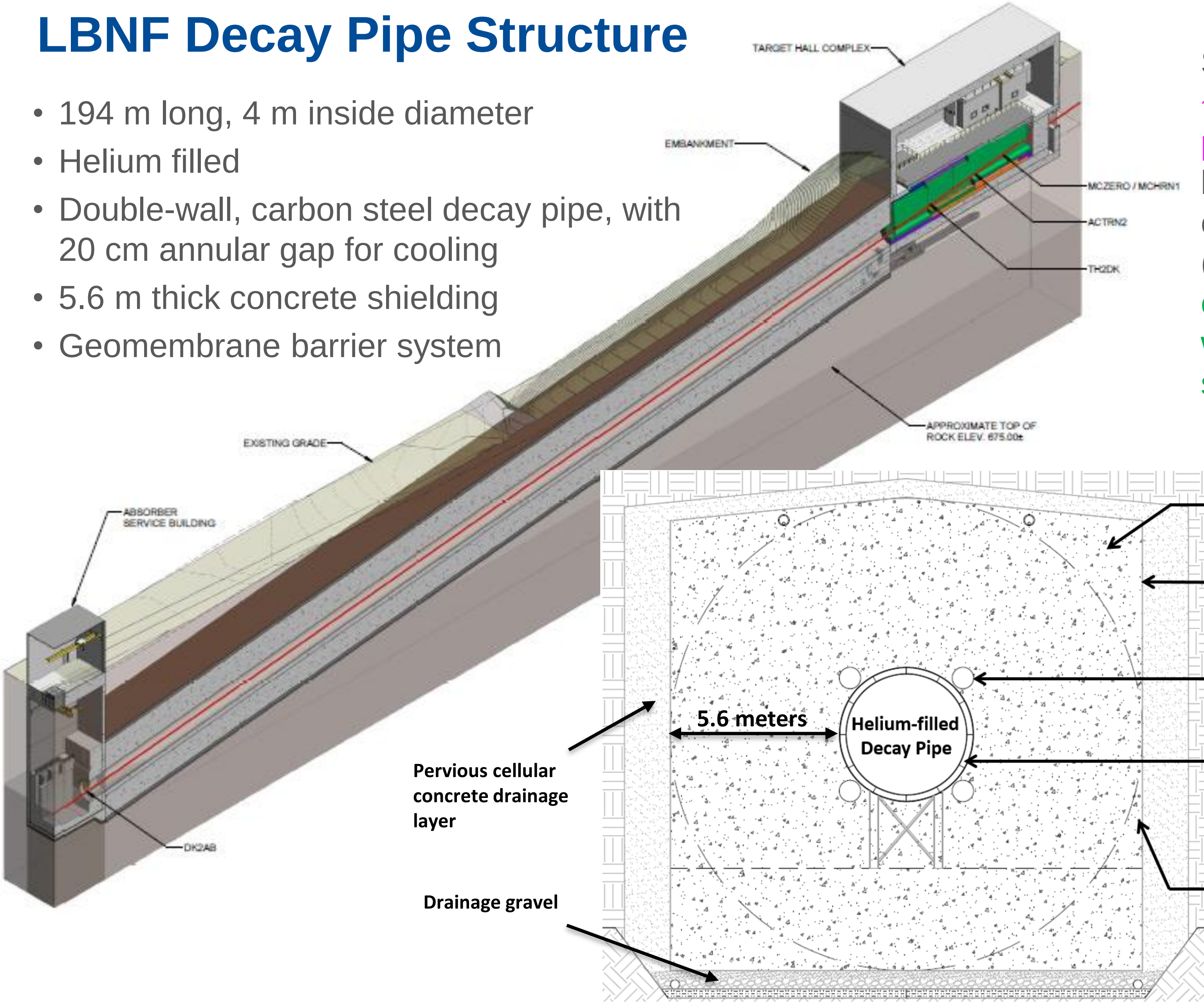
T_{max} = 149.6°C

~96% of the heat is extracted by the Platecoil and ~4% by the N_2 gas cooling.

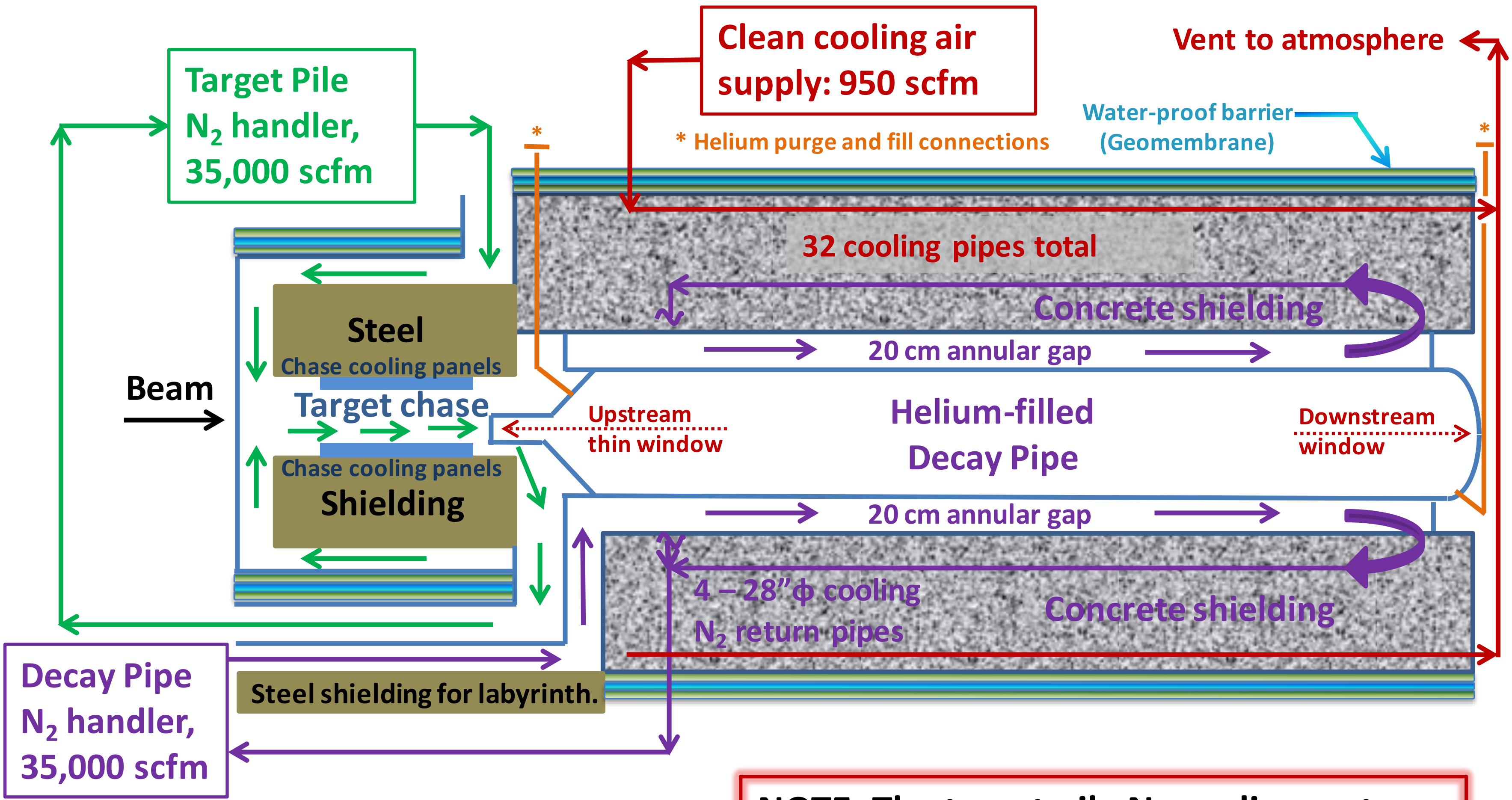
LBNF Decay Pipe Structure

- 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
- Geomembrane barrier system

System collects ~23% of the beam power, removed by a nitrogen cooling system (avoiding water cooling pipes where we cannot service them)



Target Shield Pile Gas Cooling Schematic

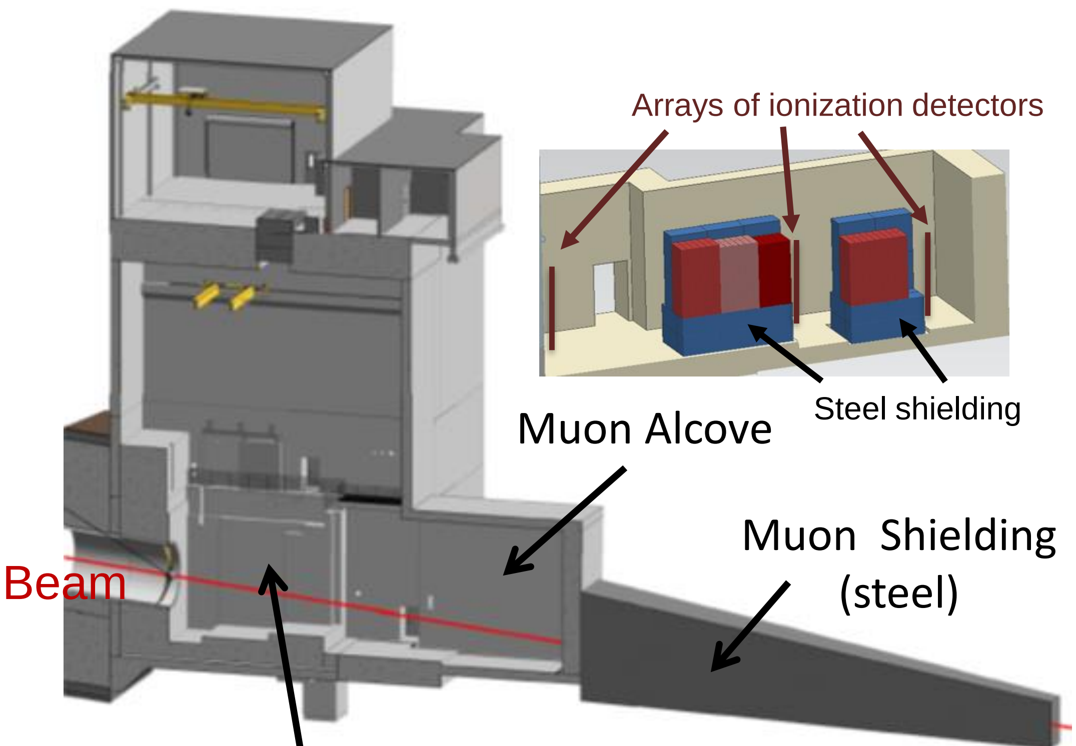


NOTE: The target pile N_2 cooling system and the decay pipe N_2 cooling system are two separate systems.

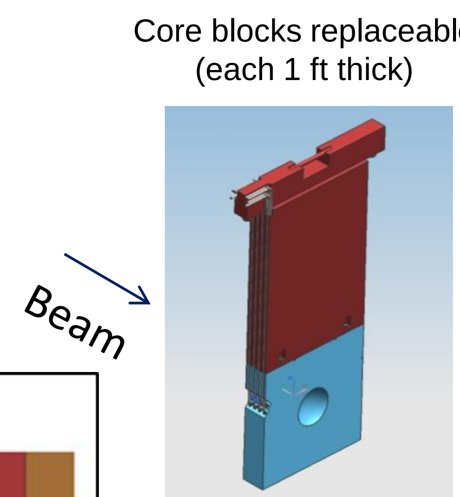
Hadron Absorber

The Absorber is designed for 2.4 MW
~ 17% of beam power in Absorber

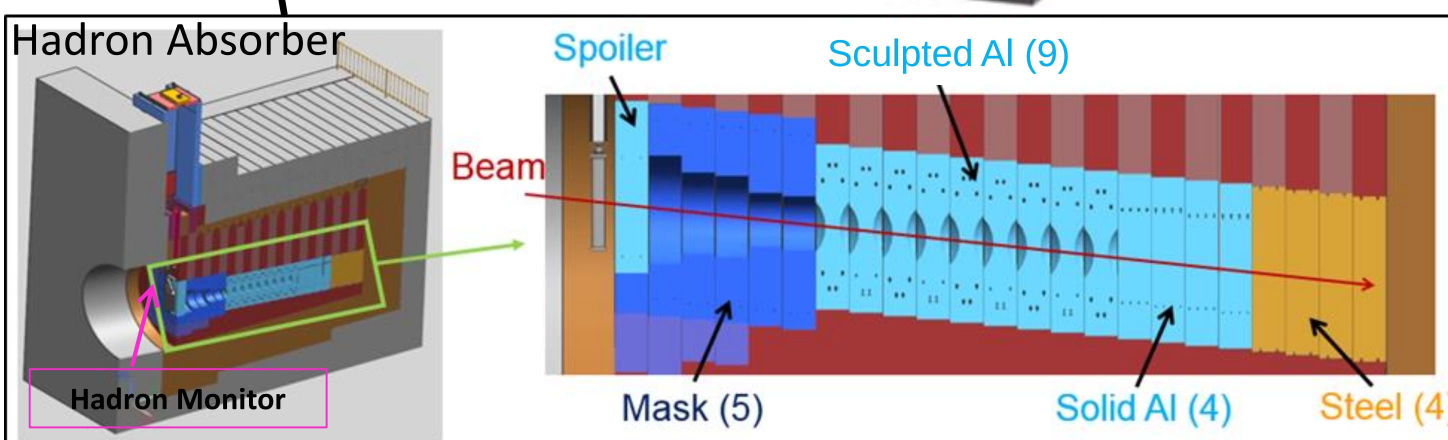
Absorber Hall and Service Building



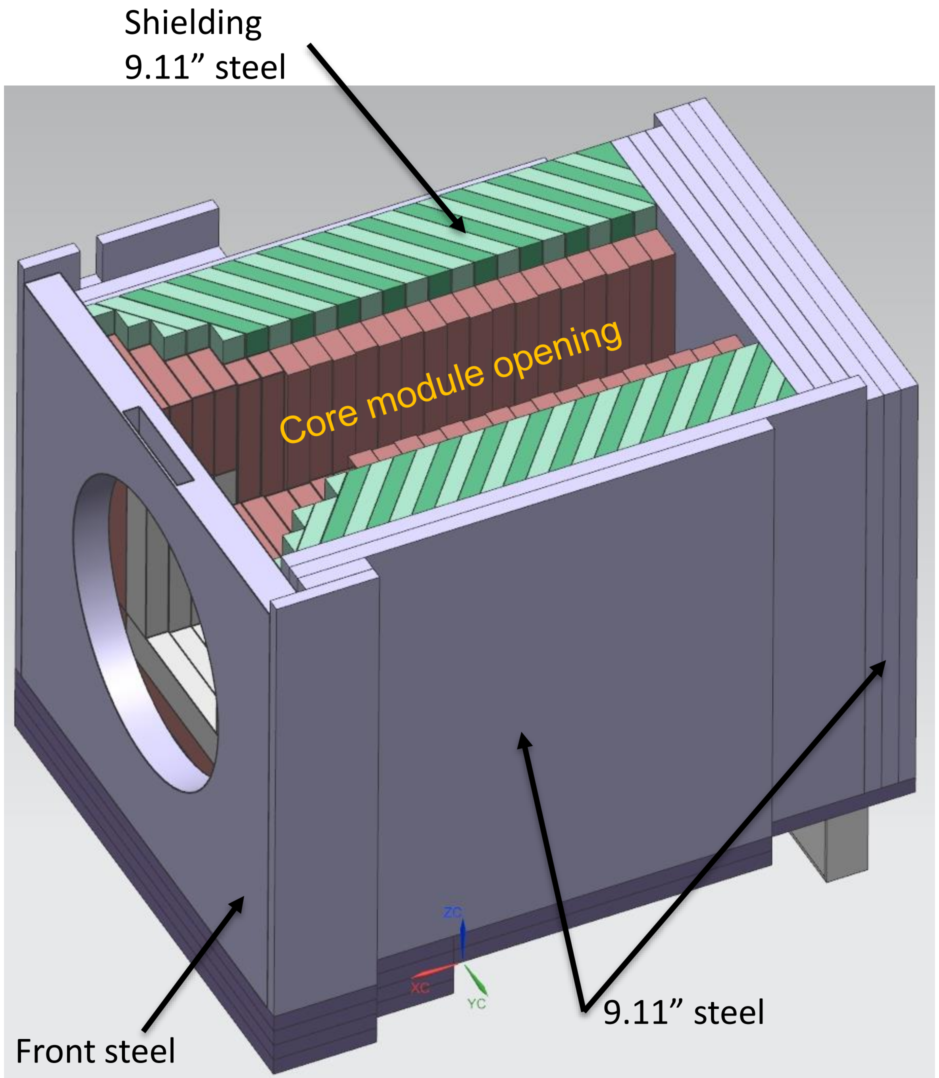
Absorber Cooling
Core: water-cooled
Shielding: forced air-cooled

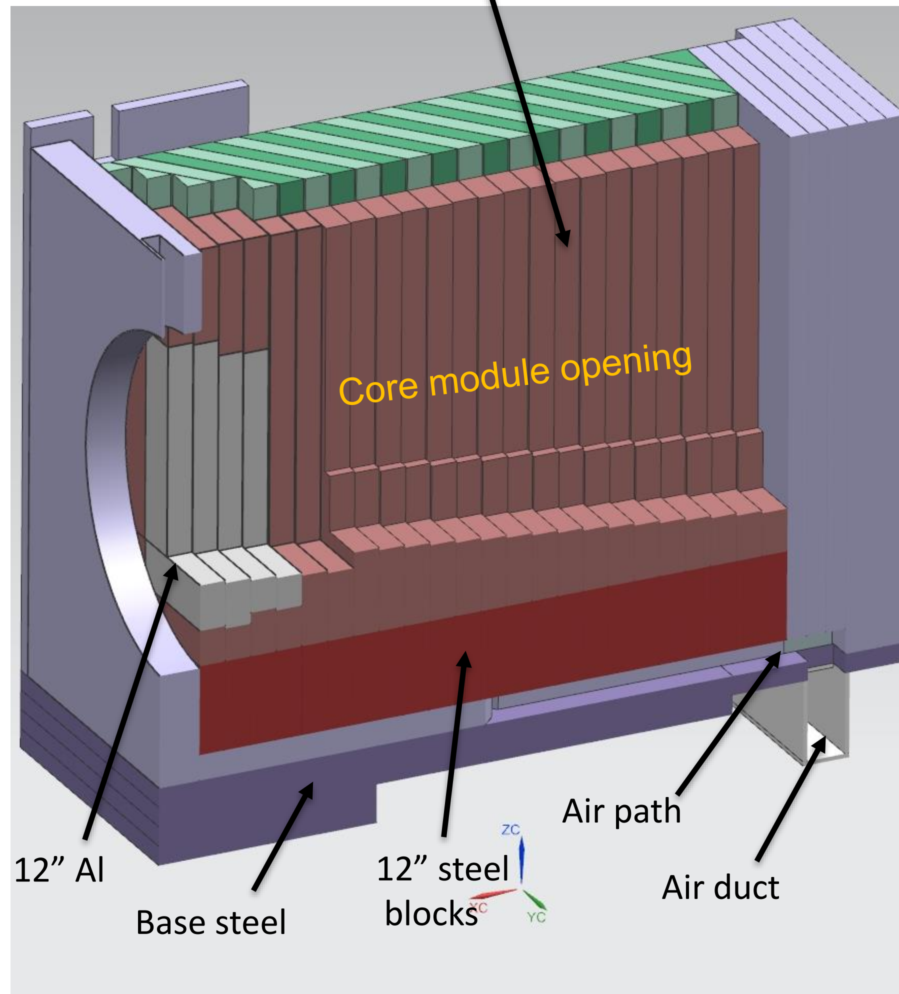


Flexible, modular design



Absorber Design – Steel Shielding





Overall dimensions (L x W x H): 355in x 285in x 295in [9m x 7.25m x 7.5m]

2.4-MW LBNF EDEP (kW) in Opt. D *vs* Ref. D

System	RD	OD	OD/RD
Target Station	951.5	1,237.7	1.30
Decay Channel	452.1	542.2	1.20
Hadron Absorber	786.0	400	0.51
4-π Neutrino power	66	69	1.05
Misc: infrastructure, binding energy & sub-threshold ptcls	144.4	151.1	1.05
Total	**2400**	**2400**	

Target and Horns of the Optimized Design

1.2 MW Optimized Design for target – cylindrical, helium cooled

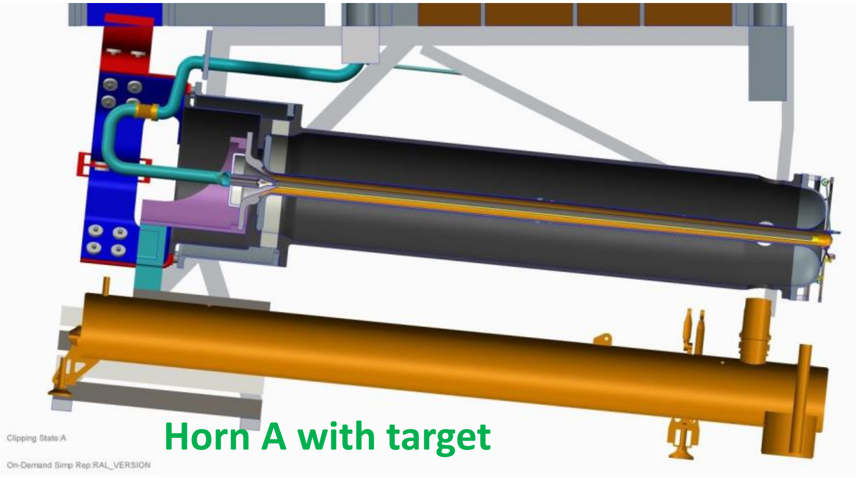
RAL report, Aug. 2017

Bafflette:
Graphite collimator, 12 cm long, to obstruct any "rogue" beam pulses in the annular area larger than the target core radius and the inner baffle radius

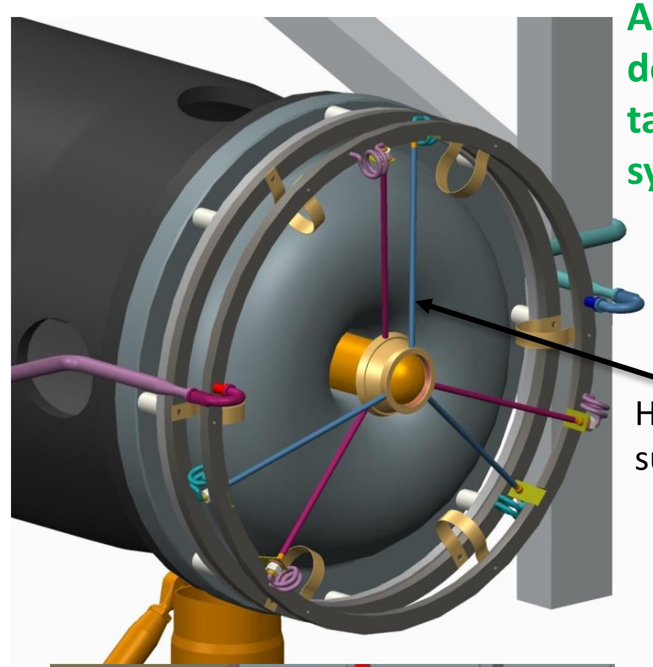
- 2.2m long (~4λ), cylindrical, segmented graphite target
- RAL conceptual design similar to successful T2K target
- Fully helium cooled
- Integral to Horn A (not a separate structure) and fully inserted
- Beam spot sigma: 2.67 mm
- Target core outer diameter: 16 mm

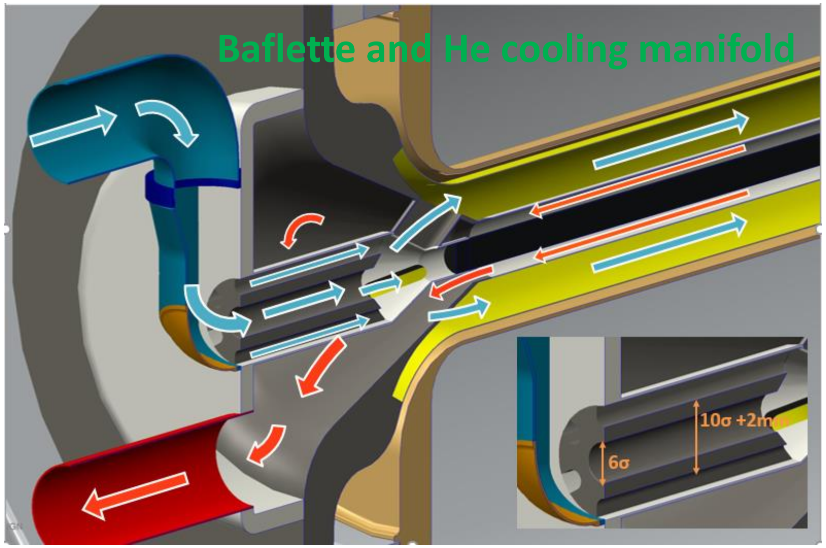
1.2 MW Optimized Design for target – cylindrical, helium cooled

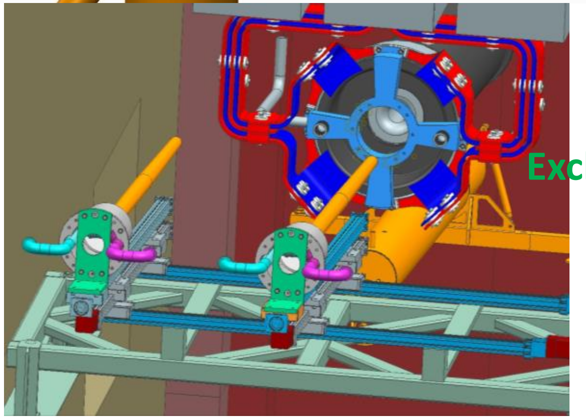
- Optimization



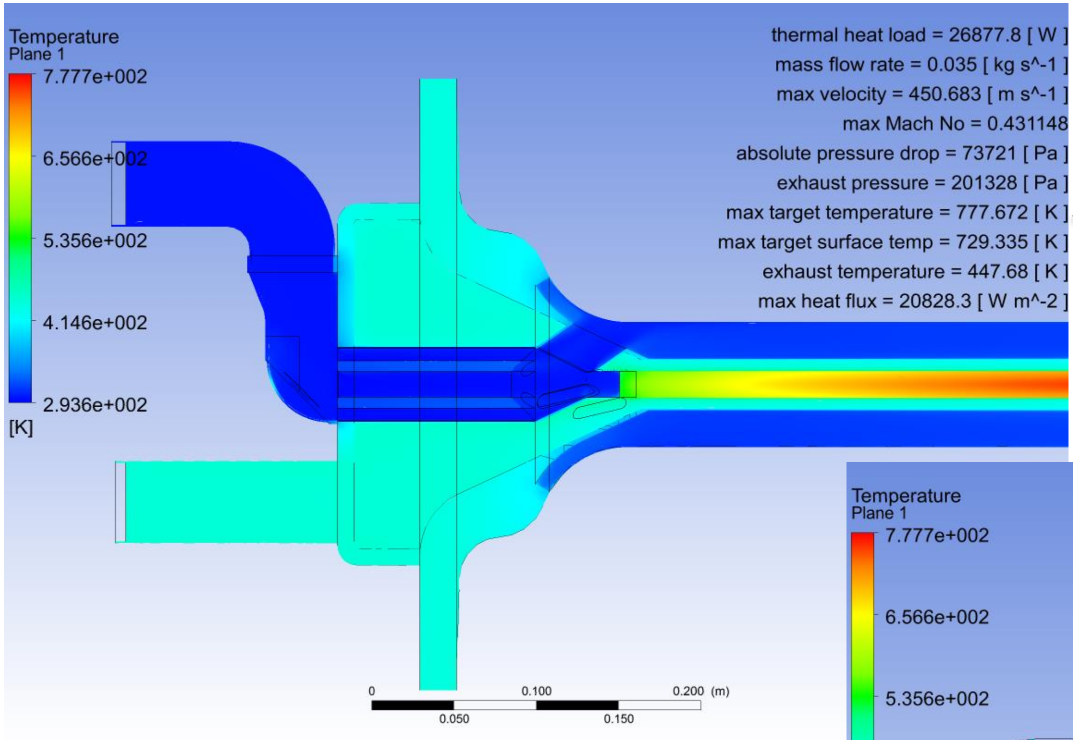
Actively cooled downstream target support system



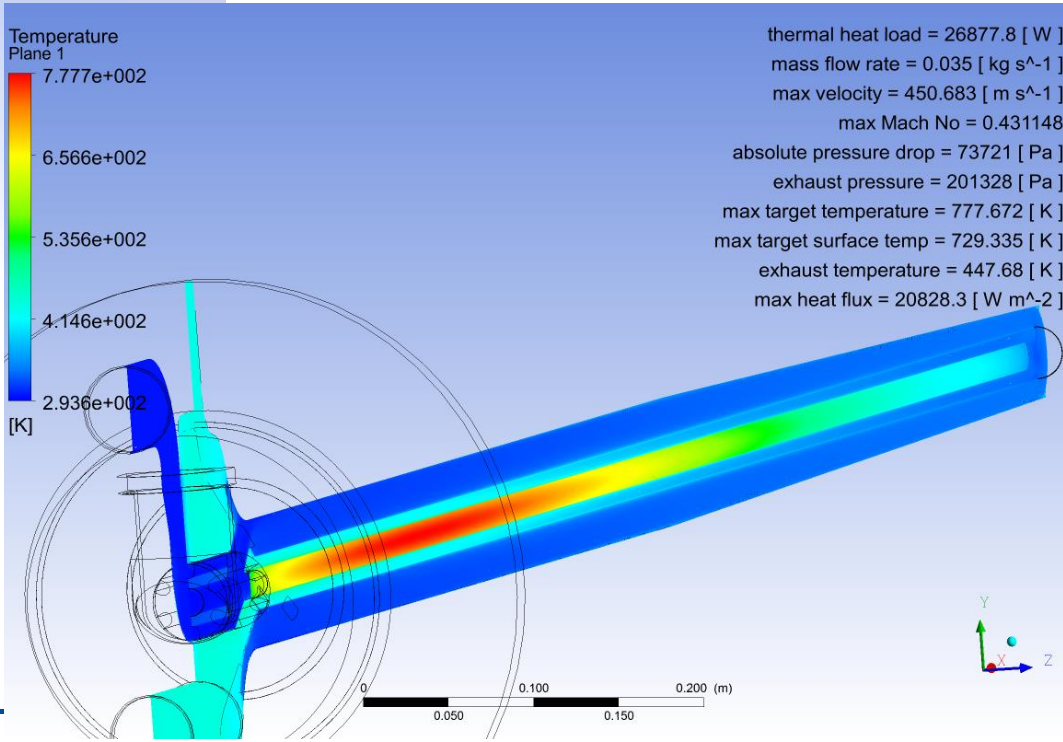




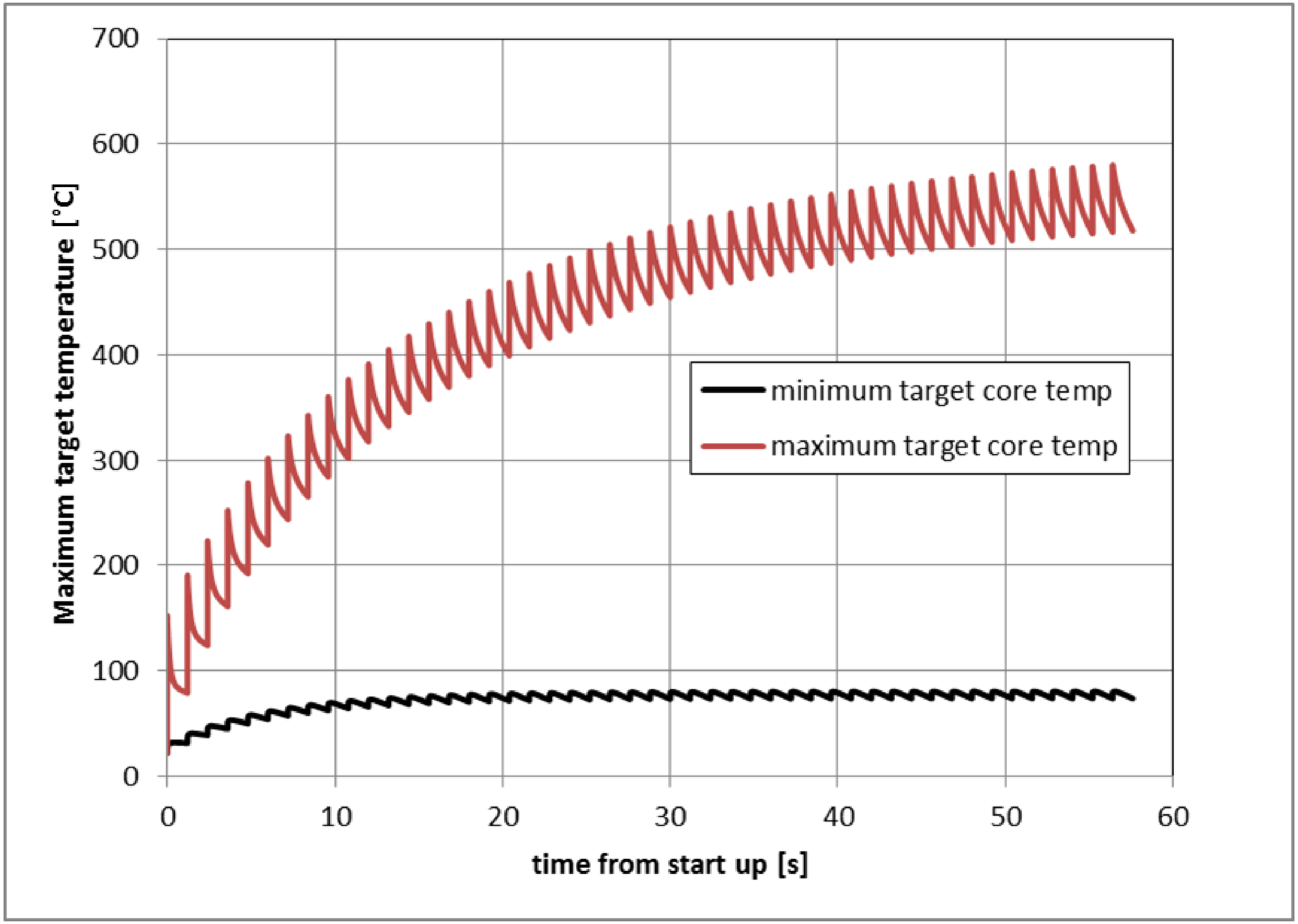
Temperatures at 1.2MW steady state simulation



504.5^{0}C

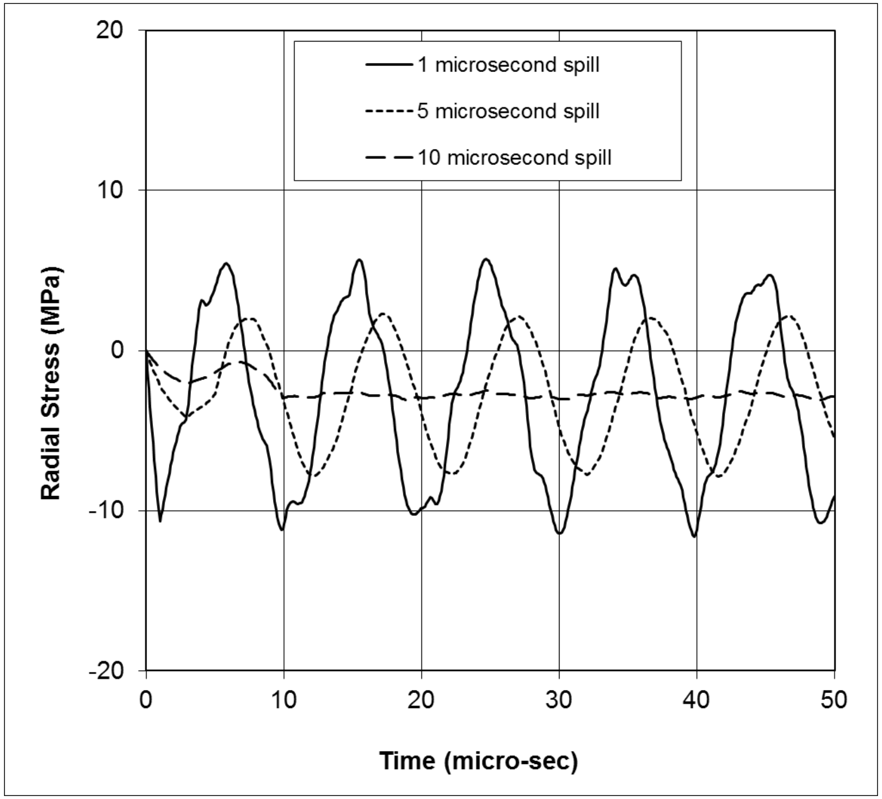


Target core temperature at 1.2MW transient simulation

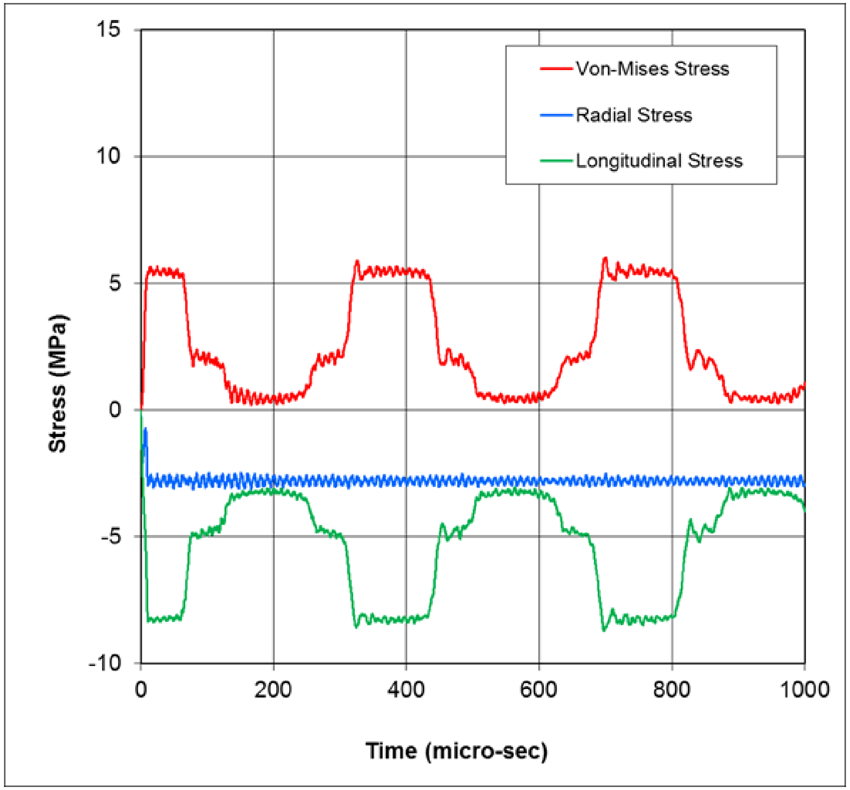


Dynamic stress response

Results for a longitudinal position close to the shower maximum in a cylindrical graphite LBNF target following a single beam spill, 7.5e13 protons, 120 GeV, beam sigma = 2.67mm, target diameter = 16 mm, target segment length = 0.45m



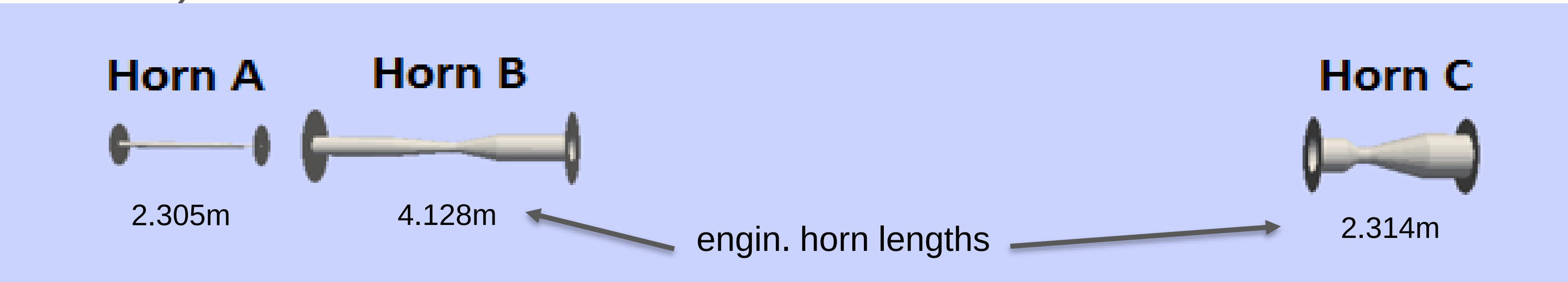
Note sensitivity of radial stress component to spill time

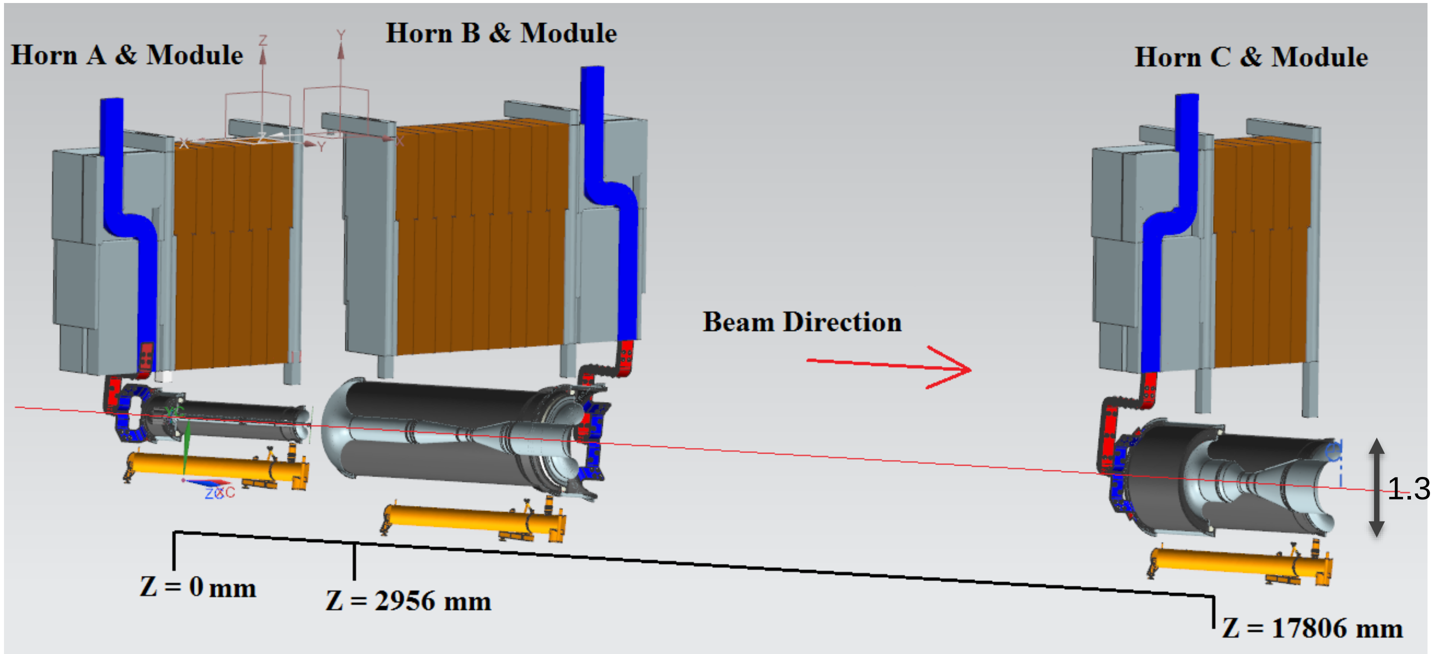


Predicted longitudinal stress oscillation is not excessive (IG43 fatigue endurance limit ~18 MPa)

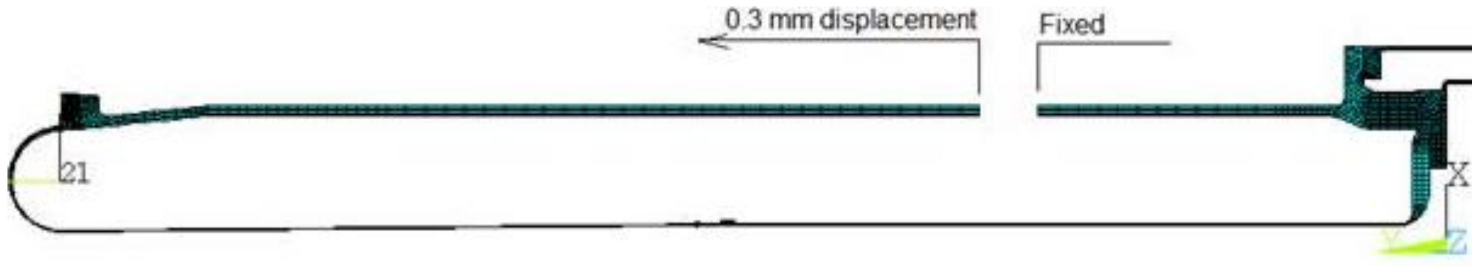
Optimized Horns

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

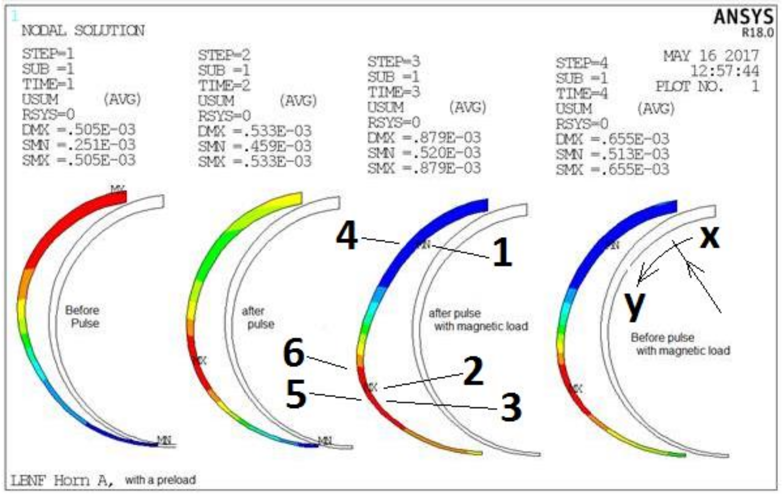




Horn A Analysis



- D.S. Transition Findings
  - Transient beam & joule heating, in addition to steady state deformation, causes large deformations & stresses.
  - Additional engineering of flange thickness, cooling rates, and preloading of inner conductor will address these issues.

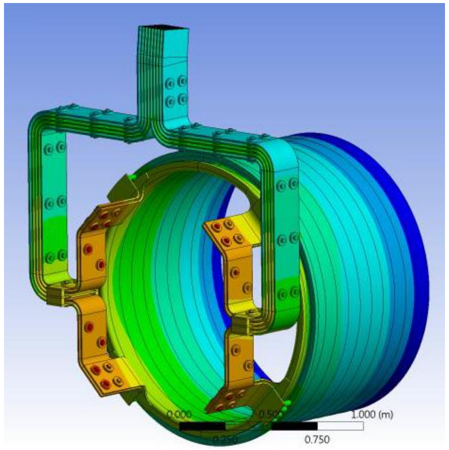


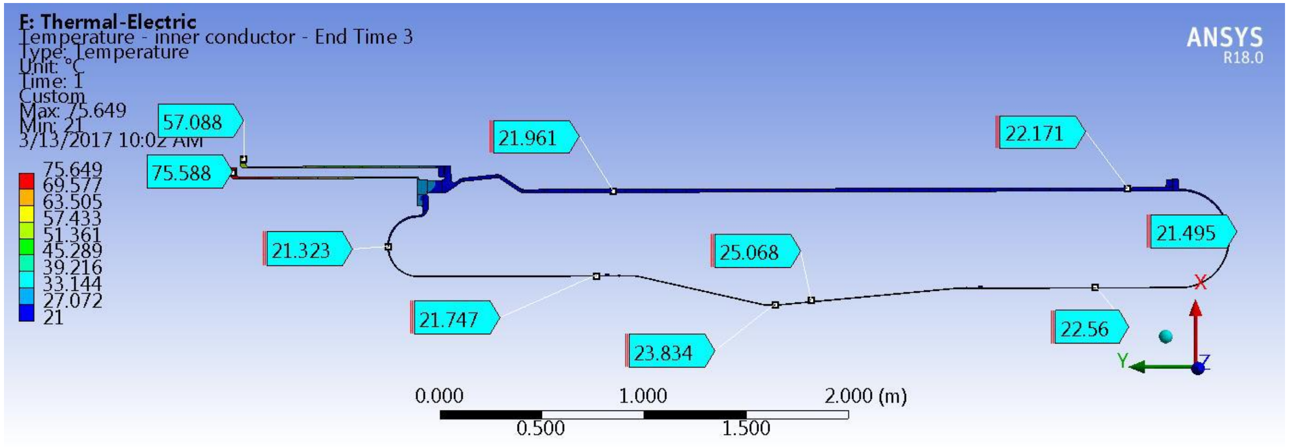
Point	Fatigue Safety Factor w/ No Preload	Fatigue Safety Factor w/ Preload
1	1.87	2.00
2	1.36	1.75
3	2.2	3.00
4	2.46	3.10
5	1.91	2.10
6	1.91	2.10

Horn B Analysis

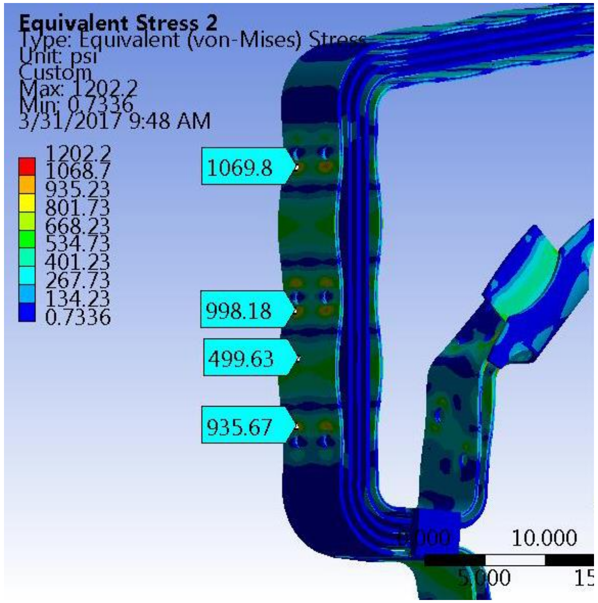
- FEA performed on conductors & equalization sections.
  - Preliminary analysis carried out for 120, 80, & 60 GeV to focus efforts.
  - 120 GeV is worst case scenario.
  - Cross-checked all thermal loads from beam heating with MARS modeling group for consistency.
- Temperatures low
- Stresses low
- Stripline is only concern

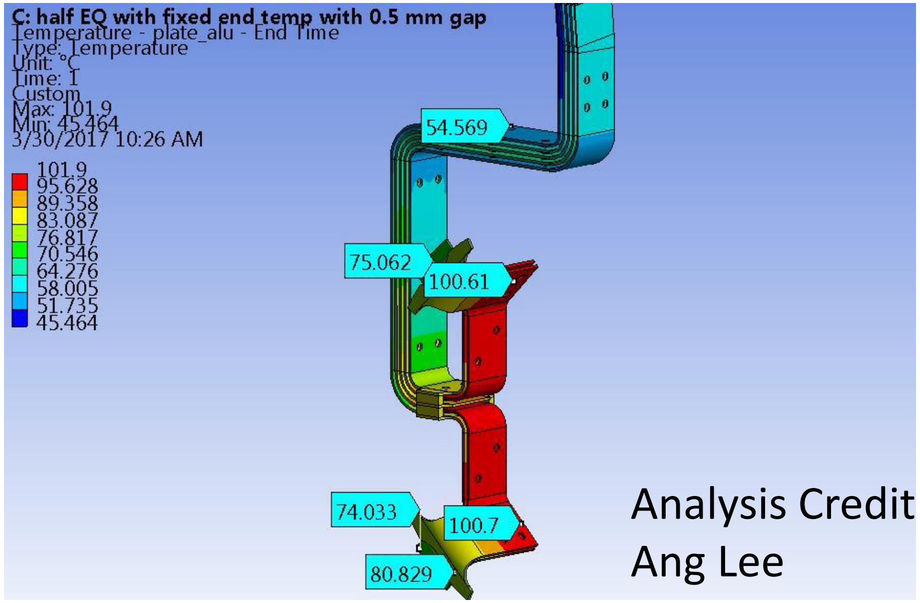
	FEA Reaction (Watts)	Cross-Check with MARS (Watts)	Comparison Ratio
120 GeV	29792	29906	~100%
80 GeV	26629	26718	~100%
60 GeV	25488	25567	~100%





Horn B Stripline Analysis





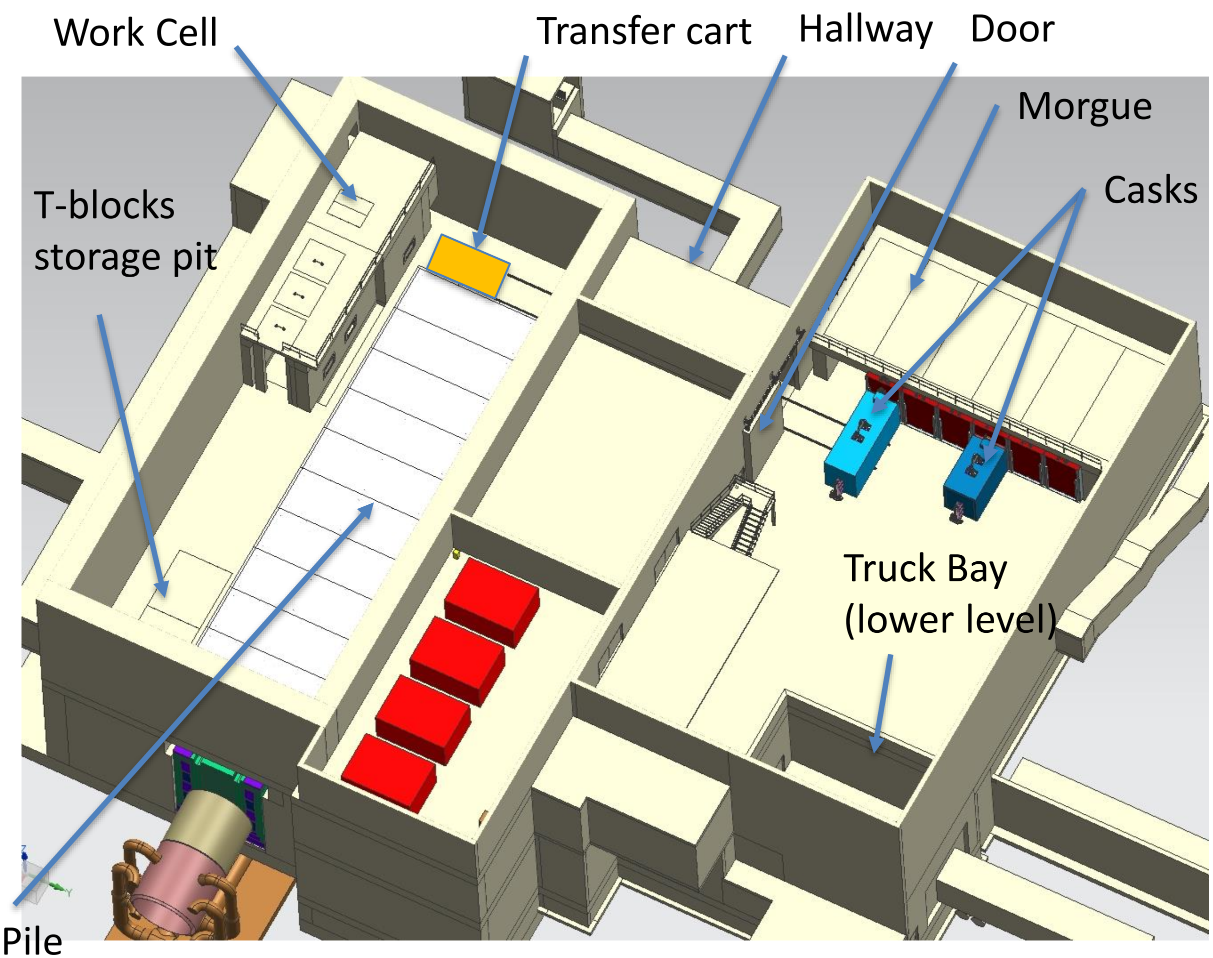
- Analyzed maximum stress & temperature
  - Stress low, not a concern.
  - Temperature higher than desired in regions of historically lower gas flow.
    - Added cooling ductwork around stripline will achieve high heat transfer.
- Focus for preliminary design
  - Connection to horn where gas cooling might need to be extended.
  - Increasing stiffness of structure due to unsupported span from horn to stripline shielding penetration.

Target Hall Complex Remote-Handling Facilities Design

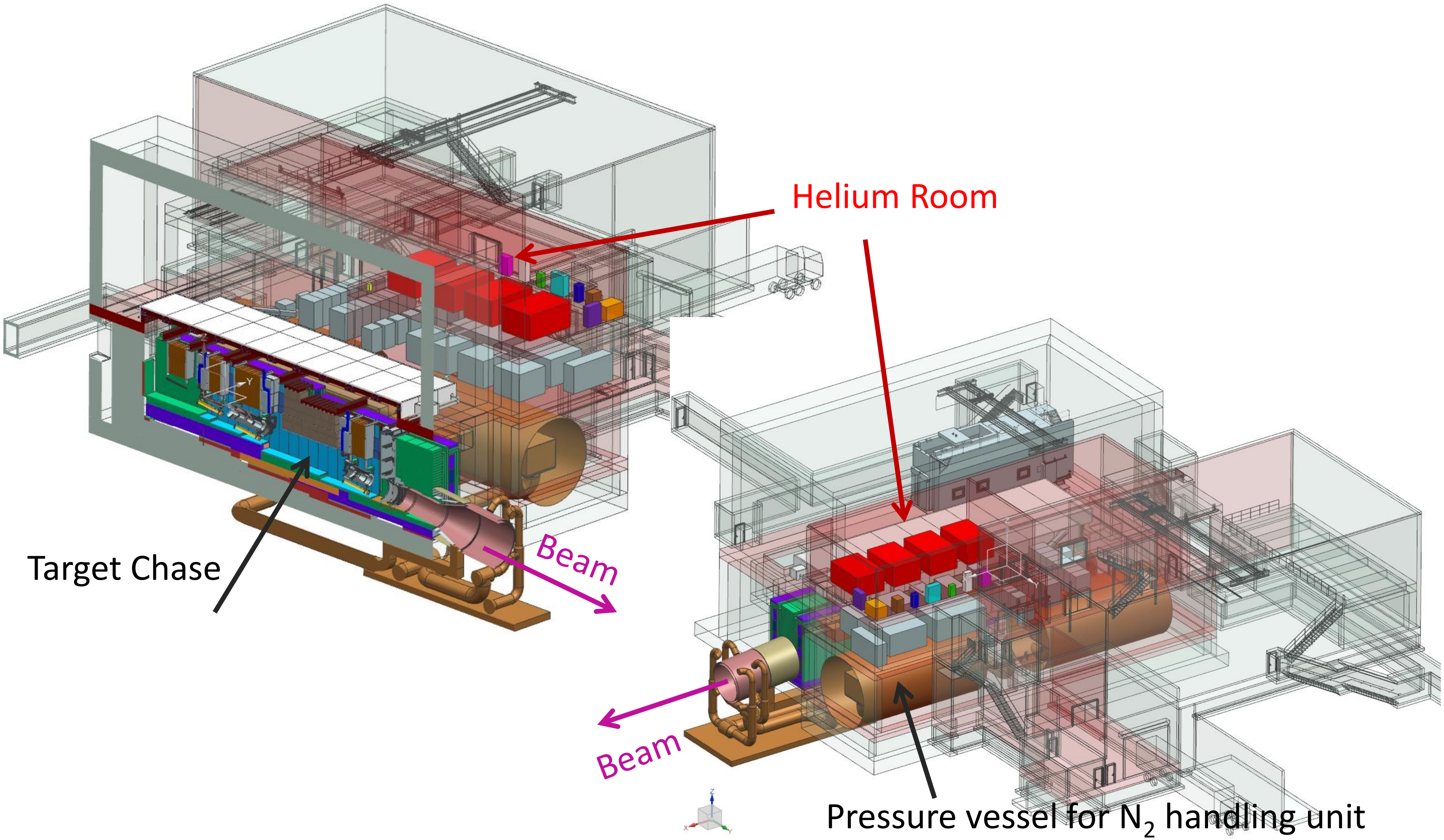
The Target Hall (left side of picture) and Service Building (right side) make up the Target Facility Complex. They are joined by a large hallway, equipped with a rail system and a sealed, shield door to enable transfer of components and casks between the two sides.

All Remote-Handling operations are provided by using the bridge cranes (60 ton) with redundant drives in both the target hall and the morgue/maintenance area.

Value engineering in progress



Target Hall Complex Conceptual Design – Optimized beamline

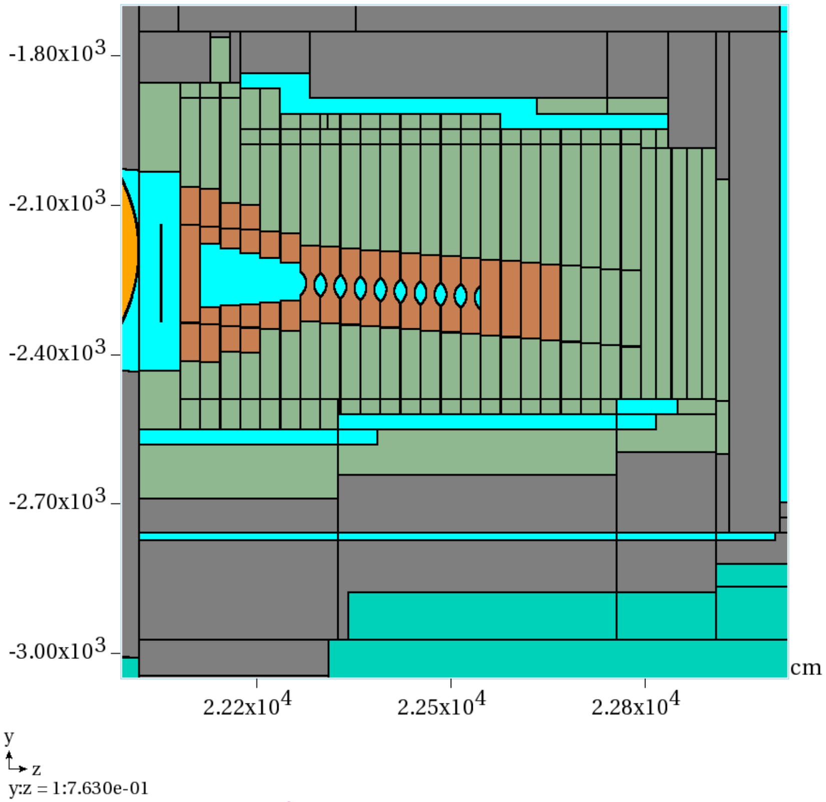


Hadron Absorber Configurations – work in progress

Taking advantage of significantly smaller EDEP in optimized design.

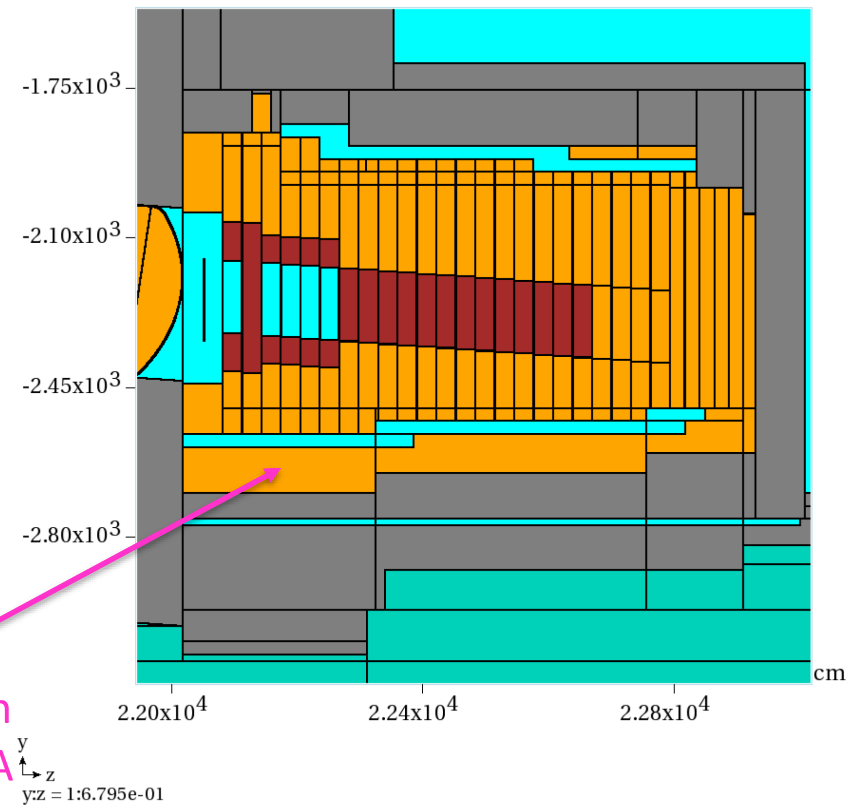
Ref. Hadron Absorber (RHA)

Non-uniformity, sculpting needed for RD



Uniform Hadron Abs (UHA)

No sculpting, larger uniform masks, larger core blocks (60”->67”), 1/16” windows on mask blocks – better for muon measurements



CFD simulation points to temperature reduction by 40% (89^0C) in the optimized design with UHA

Cost of the optimized Beamline – Technical Components and Conventional Facilities

- The cost below includes DOE and non-DOE contributions.
- Costing performed assuming DOE accounting for all systems.
- Cost presented as Budgeted Cost for Work Scheduled (BCWS) and does not include contingency.
- Cost of Technical Components is ~$191 M.
- Cost for Beamline Conventional Facilities is ~$266 M.
- The combined cost of the optimized Beamline (~$457 M) is expected to be $34 M more than the cost of the Reference Design Beamline.
- It is expected as well that the optimized Beamline will require six more months to be ready in comparison with the Reference Design Beamline.
- Approximately one third of the cost of the technical components is assumed to be provided by non-DOE contributions.

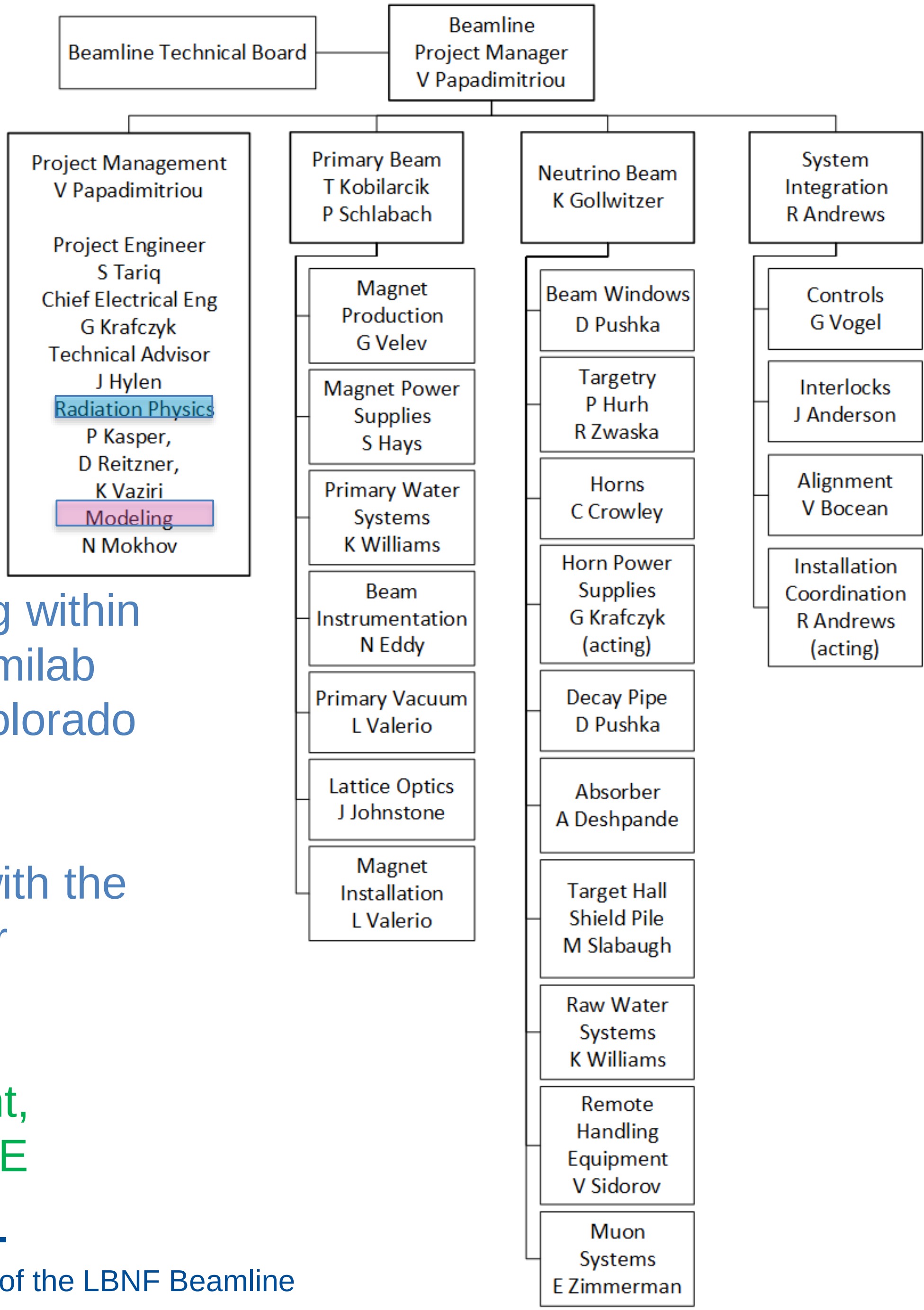
Challenges and R&D issues

- Support a ~2 m long target without sagging and be able to replace it as it fails.
- Fabricate long horns (Horn B) to high tolerances to reduce beam related systematic errors (nickel coating, etc.).
- Design the beamline in such a way that it is relatively easily reconfigurable (tau appearance studies in the future, etc.).
- Availability of concentrated resources and funding uncertainties.
- Can we assume higher up-times by running longer? Do we want to take profit of the CW linac and make room for additional high power facilities? – work more on tritium related R&D.
- Hydrogen and Oxygen recombination R&D - catalyst. (Argon within NuMI horns; helium in T2K horns; Argon or helium in LBNF horns and more water there for cooling than NuMI.)
- Target materials R&D (RADIATE, etc.)
- ……………………………………..

Project Team and International Partners

Beamline Project Organization & Staffing

- 4 L4 Systems, 21 L5 Systems
- A 22 member Technical Board



- There are additional colleagues working within the Beamline Team from almost all Fermilab Divisions and Sections and the U. of Colorado and Drexel.
- The Team has a lot of experience with NuMI/MINOS, NuMI/NOvA as well as with the Booster Neutrino Beam and accelerator operations in general.
- International Partners.
- The TB includes Beamline management, subject matter experts, and LBNF/DUNE management.

Members of the Fermilab Beamline Team

- P. Adamson
- J. Anderson
- K. Anderson
- R. Andrews
- J. Angelo
- D. Barak
- V. Bocean
- C. Crowley
- A. Desphande
- N. Eddy
- H. Friedsam
- C. Gattuso
- K. Gollwitzer
- T. Hammernik
- L. Hammond
- B. Hartsell
- S. Hays
- A. Helander
- D. Hixson
- P. Hurh
- J. Hylen
- C. Jensen
- J. Johnstone
- T. Kobilarcik
- P. Kasper
- G. Krafczyk
- A. Lee
- P. Li
- T. Lundin
- A. Makarov
- A. Marchionni
- N. Mokhov
- R. O'Sullivan
- V. Papadimitriou
- D. Pelletier
- D. Pushka
- I. Rakhno
- D. Reitzner
- M. Sawtell
- P. Schlabach
- V. Sidorov
- M. Slabaugh
- A. Stefanik
- S. Striganov
- Z. Tang
- S. Tariq
- I. Terechkine
- D. Tinsley
- I. Tropin
- L. Valerio
- K. Vaziri
- G. Velev
- G. Vogel
- K. Williams
- C. Worel
- M. Yu
- B. Zwaska …..

The Team is enhanced by a Technical Board and a Beam-simulation group (M. Bishai, L. Fields, P. Lebrun,…) and several other colleagues across Divisions, Sections and Centers

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

International Partners

- IHEP/China:
  - Corrector magnets for primary beamline – prototype and 23 production magnets (I-CRADA signed in March 2017). Prototype testing complete.
  - 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 (recent positive news on ~ $8M allocation to Beamline by STFC):
  - Target R&D.
  - Target design and production.
  - Associated package for target support systems (e.g. remote handling)
  - Possibly, telemanipulator for target and helium system for target

- In discussions with KEK/Japan. For the time being committed on:
  - Prototyping of the seal of target shield pile's hatch covers
  - Prototyping of the sealed feed-through for the horn striplines

- Exploring possibilities for collaboration with several other partners.

Milestones

International Project Milestones (IPM) established in October 2017 instead of stakes in the ground that were used earlier:

International Project Milestone	Date
Start Detector #1 Installation	June 2022
Start Detector #1 Operations	January 2025
Start Detector #2 Installation	June 2023
Start Detector #2 Operations	June 2026
Beam Ready	September 2026

These milestones were established by LBNF and DUNE leadership in collaboration with DOE and Fermilab leadership to facilitate coordination between project and experiment and across International Partners.

These are being monitored against Working Project Milestones (WPM).

By CD-2 IPMs and WPMs will be re-aligned.

Milestones and plan forward

- Preliminary design for the Beamline was expected to start in October, 2017.
- Did not get yet sufficient funding in FY18 and are currently delaying the start of the Preliminary Design to the beginning of October, 2018.
- Project would like to - and has been advised to – be baselined as early as the end of 2019/early 2020.
- Construction at the Fermilab Site is expected to start in 2020/2021.
- We currently expect to require a 21 month shutdown (for the Main Injector). Beamline 1.5 months in the beginning; Conventional Facilities 12 months; Beamline 7.5 months in the end. The long shutdown in the working schedule starts within 2025.

Summary and Conclusion

- The LBNF Beamline Team has recently completed the conceptual design, cost and schedule for a beamline further optimized for the physics.
- The main changes are in the Targetry and Horns systems but there are significant impacts on some other systems as well (Remote Handling, Conventional Facilities, etc.).
- There are a couple of staging options available, if necessary.
- We are technically ready to start the preliminary design – current expectation to start in FY19.
- Several interesting and challenging design issues ahead.
- We are very interested to increase the international participation and very interested to increase the Fermilab participation as we start the preliminary design.