Status of the LBNF beamline

Tristan Davenne for the DUNE collaboration
Rutherford Appleton Laboratory
Science & Technology Facilities Council

The 19th International Workshop on Neutrinos from Accelerators

25-30 September 2017

Uppsala University Main Building

Fermilab CERN Sanford Underground Research Facility U.S. Department of Energy Office of Science DUNE

LBNF = Long Baseline Neutrino Facility

Takes protons from Fermilab accelerator

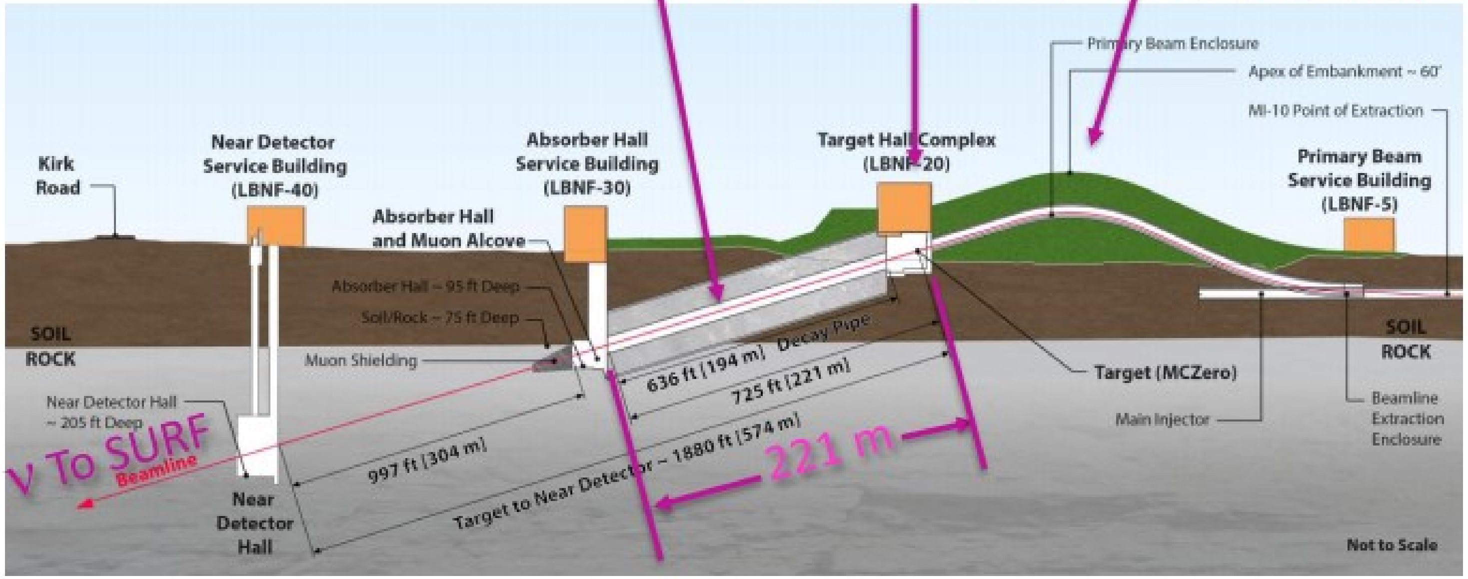
Produces beam

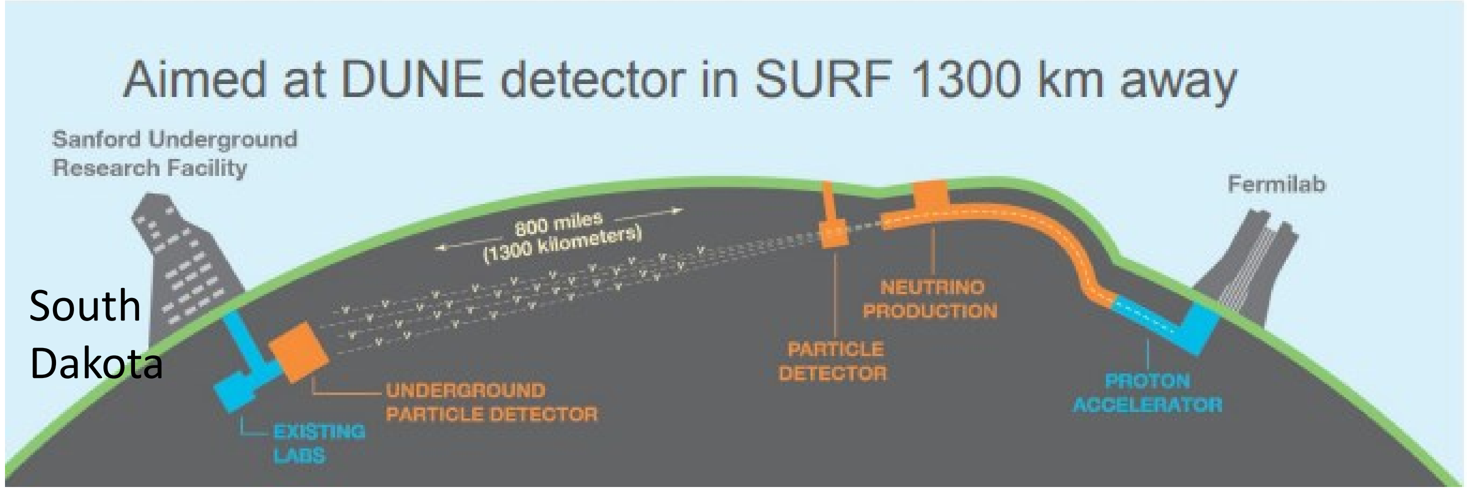
of ν_μ or $\bar{\nu}_\mu$

π -> ν decay

Target & Horn Focusing

Protons (tunable 60 GeV to 120 GeV)





Study neutrino oscillation phenomena

Drivers for LBNF beamline design

The primary science objectives of DUNE are[2]

- A comprehensive investigation of neutrino oscillations to test CP violation

$\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu_e}$

- Determine the ordering of the neutrino masses
- Search for neutrinos beyond the currently known three

Beam Requirements:

- Produce as many neutrinos as possible around oscillation peaks (0.8GeV & 2.4GeV for L=1300m)
- Beam pointed at detector, rather than off-axis (T2K and NOVA)
- Toroidal horn magnetic field to achieve ν vs $\bar{\nu}$ selection by beam focusing π^+ or π^-

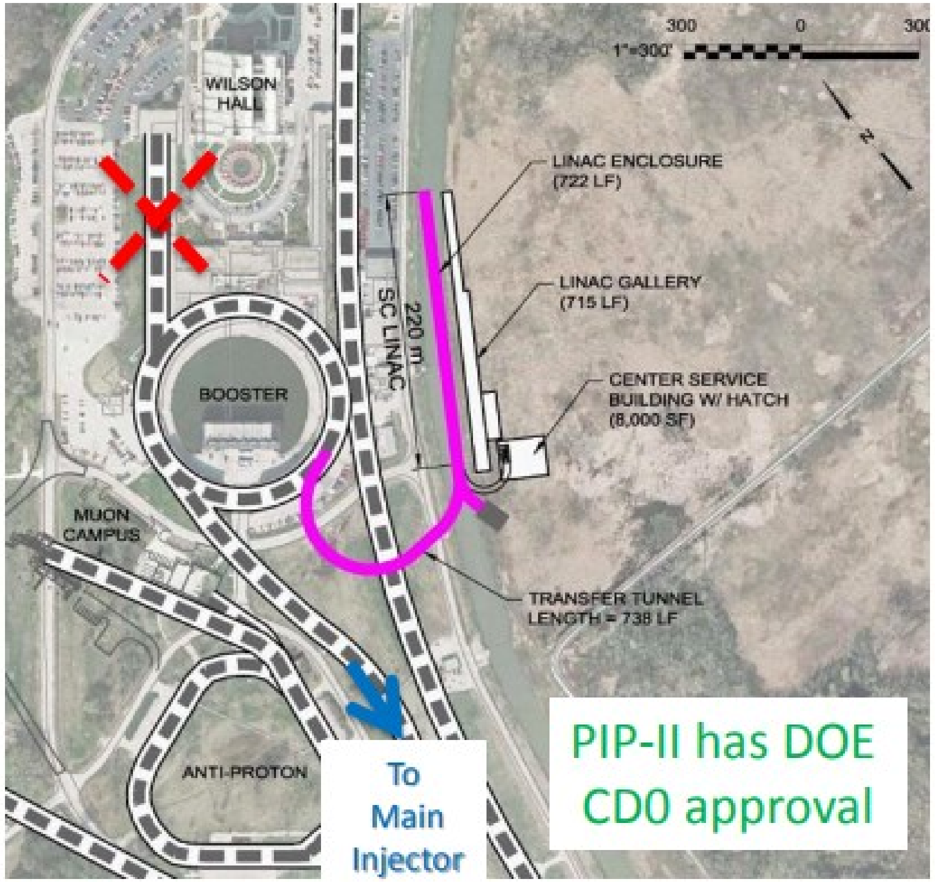
Detector and beam will run for decades

- Include flexibility to modify beam-line, e.g. for higher Energy
- Implies possibly different target/horn shapes and locations

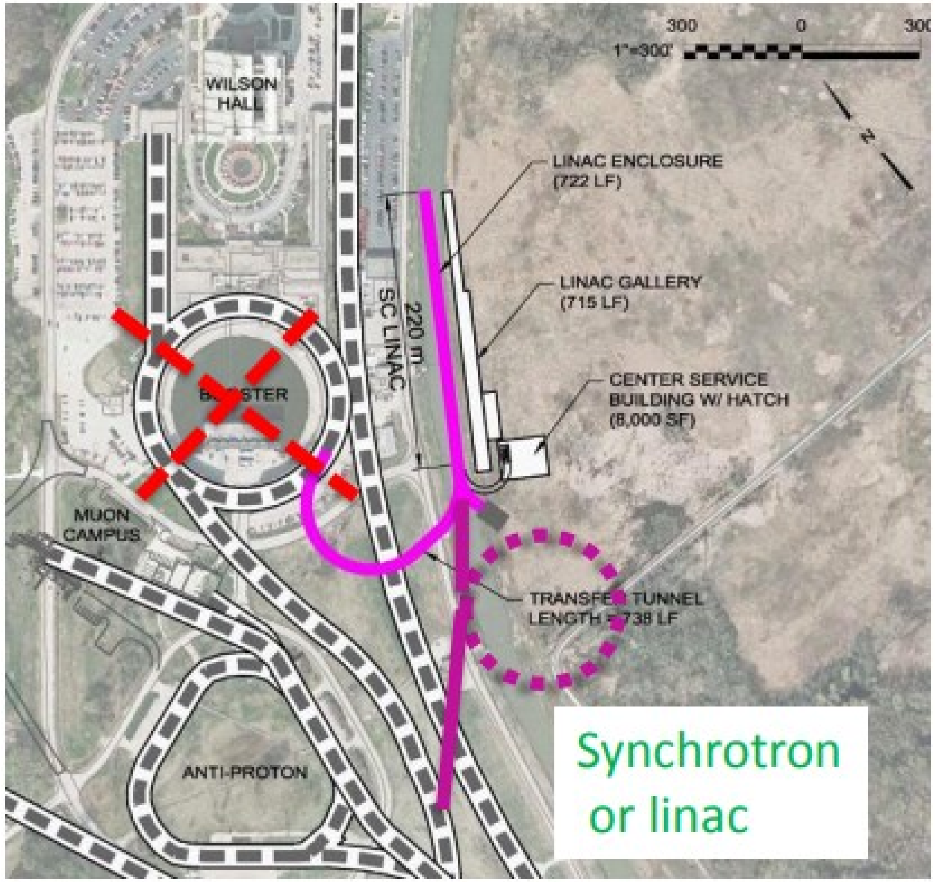
Accelerator stages: Linac -> Booster -> Main Injector -> *beamline*

Fermilab NuMI neutrino beam recently upgraded; under Proton-Improvement-Plan I (PIP-I) went from 0.4 MW to 0.7 MW proton beam power (*achieved this year !*)

- LBNF to start operation at 1.2 MW with PIP-II new linac to Booster
- LBNF designed for upgrade to 2.4 MW with PIP-III replacement for Booster



LBNF initial target & horns for 1.2 MW

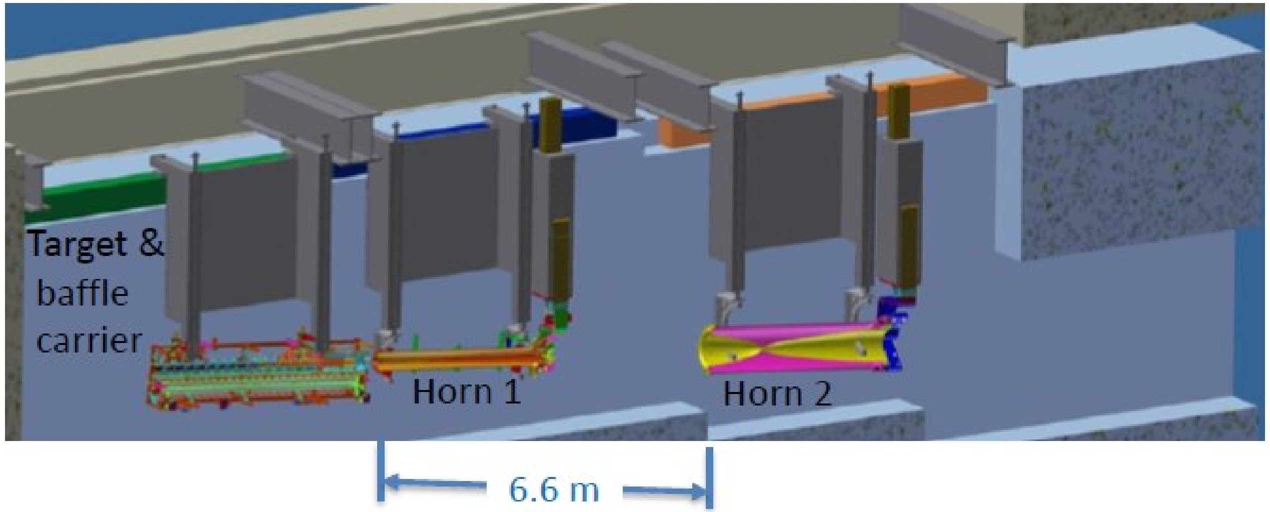


LBNF permanent parts 2.4 MW capable

Two different beamline designs under consideration
2015 reference design & 2017 optimized design

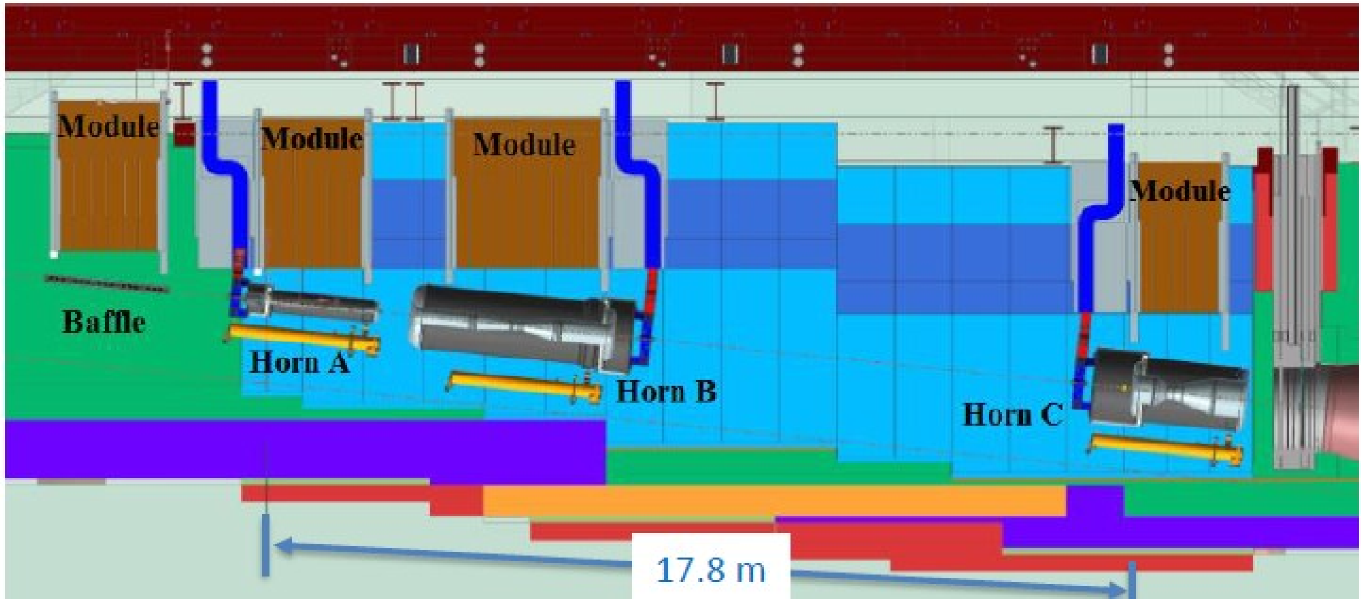
CD-1 Reference lower-cost starter, based on proven NUMI tech, …upgraded/replaced later

- 2 horns
- 1 m long target
- Target inserted 2/3 way into horn 1



Optimized design recent optimized configuration for DUNE CP violation

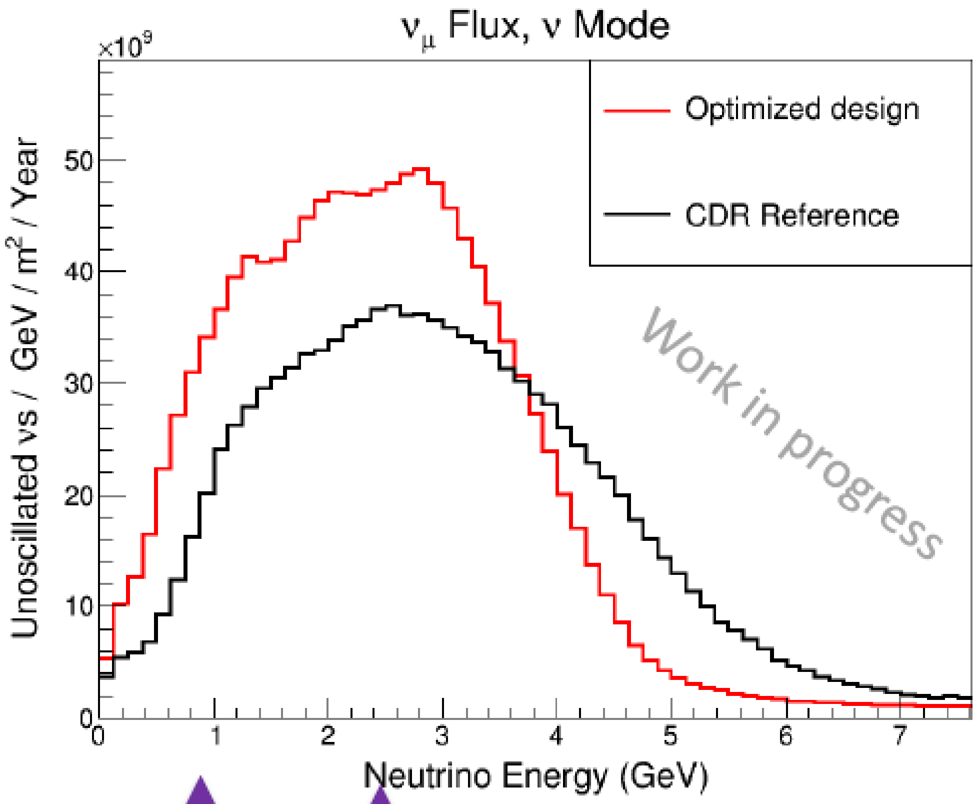
- 3 horns
- 2 m long target
- Target mounted entirely in horn A



Optimized staged

- start with just 2 of the 3 optimized horns

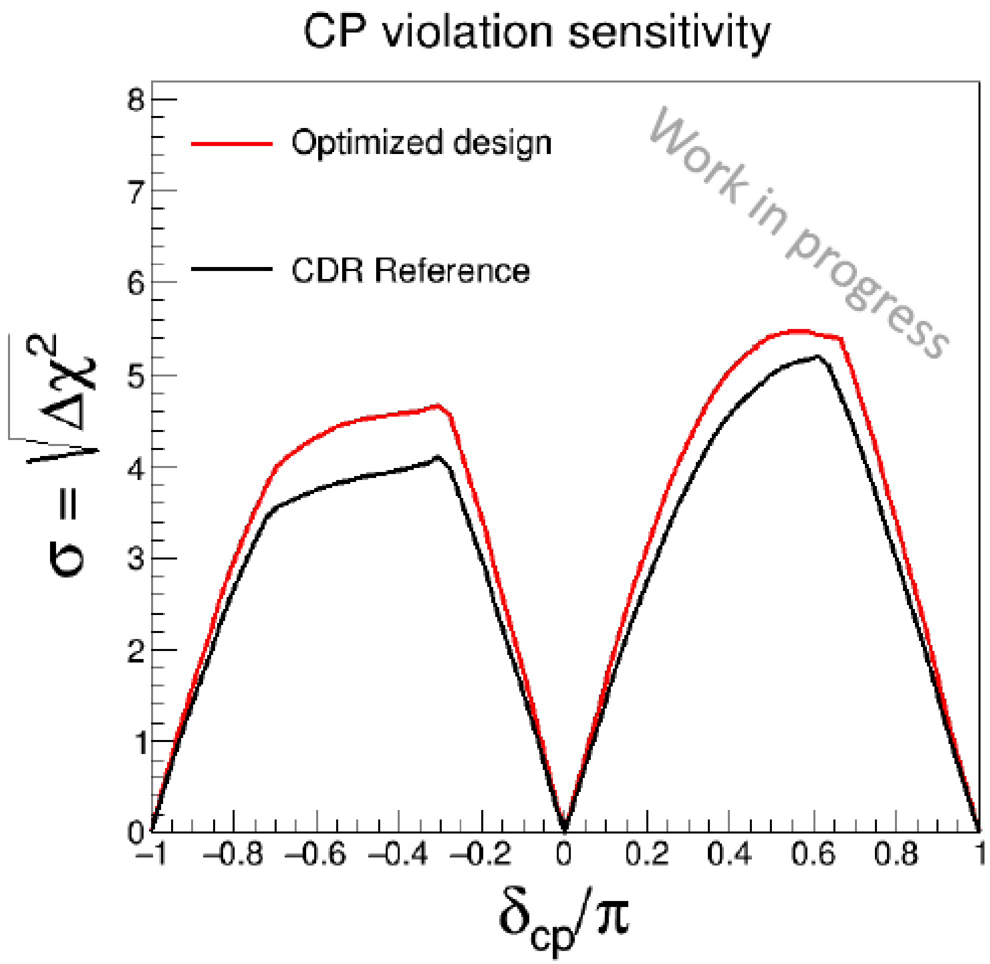
Optimized versus reference design



2[nd] and 1[st] oscillation max.

Sensitivity for (detector) x (beam) of 300 kT MW years exposure

- includes derating for beam down-time
- DUNE reference = 40 kT detector



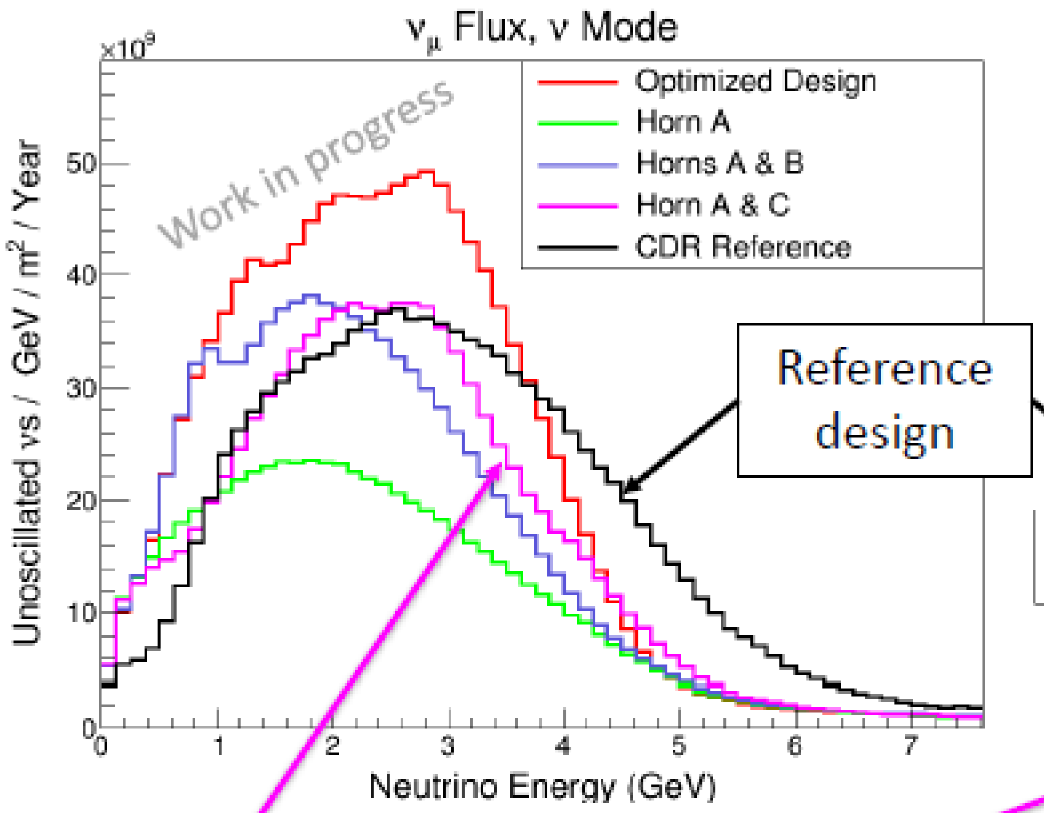
Optimized system:

- Increases flux in oscillation region
- Decreases flux in high-energy tail
- Increases CP sensitivity

Rowan Zaki

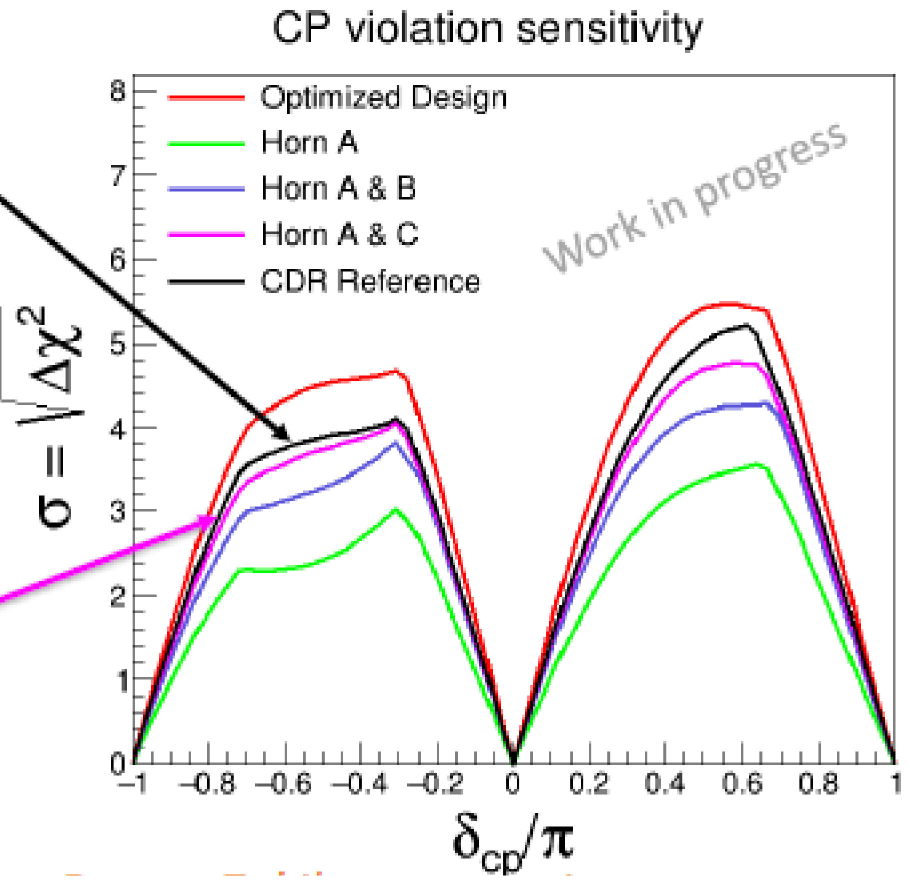
Beam-line Staging possibility

If do not have resources for fully-optimized beam at start



Sensitivity for detector x beam of 300 kT MW years exposure

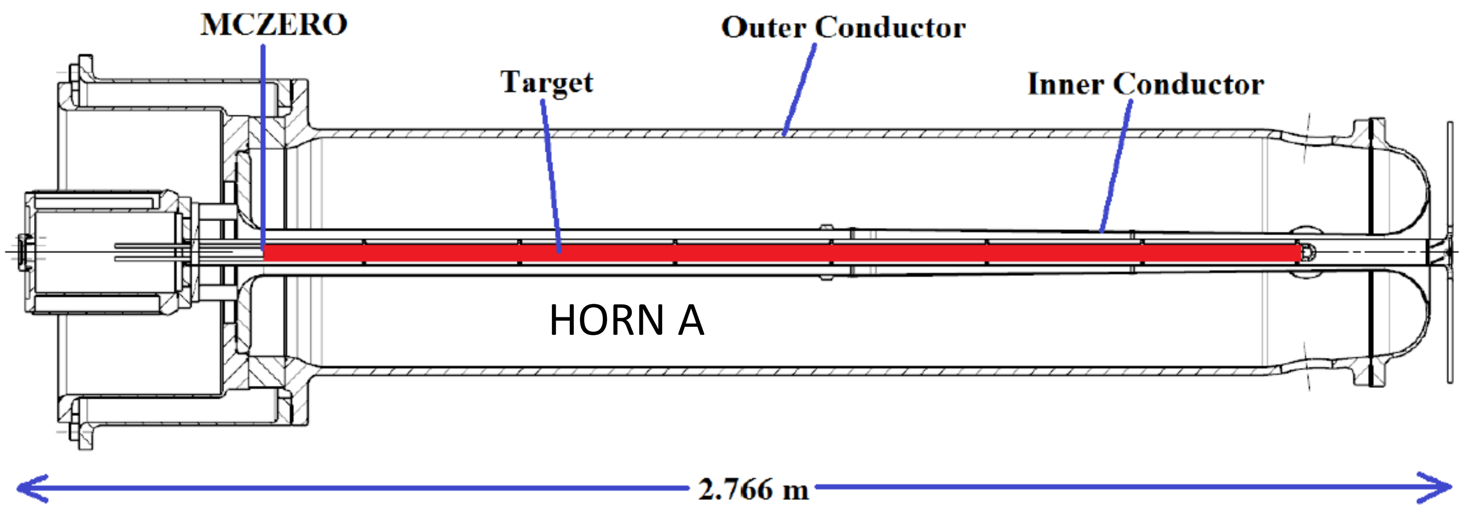
- includes derating for beam down-time
- DUNE reference = 40 kT detector



Using horns A&C from optimized design is nearly as good as the 2-horn reference design

- would allow much easier later upgrade to fully optimized

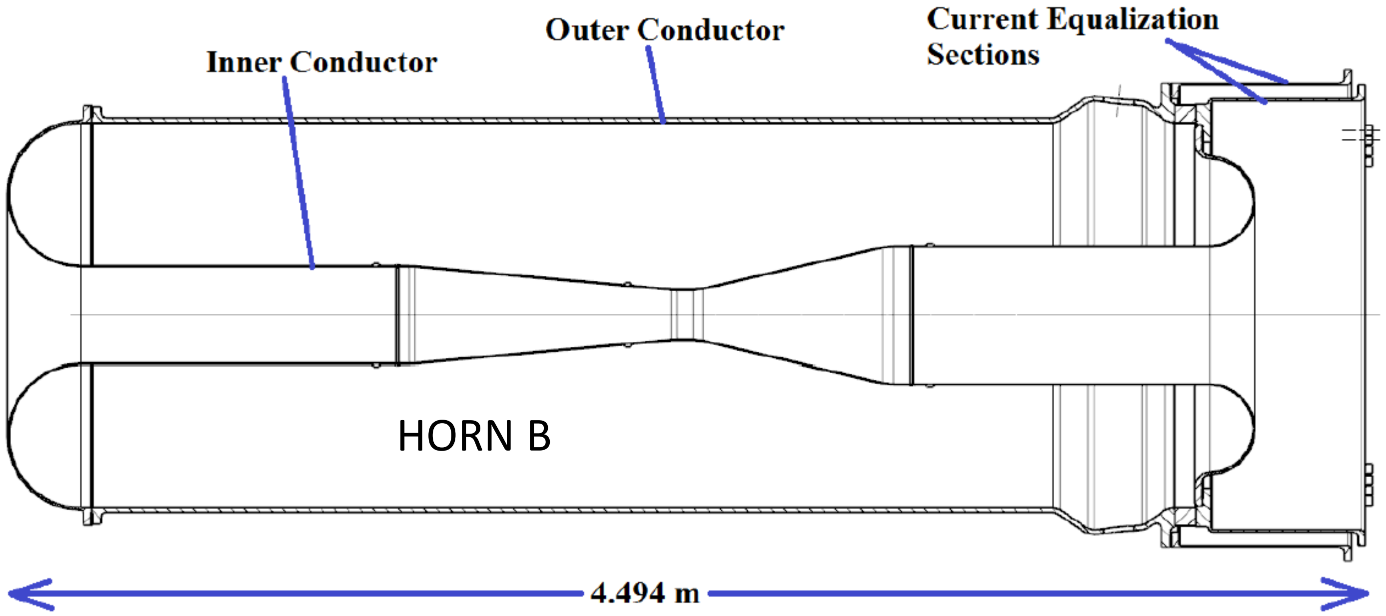
Optimized Horn designs for 1.2MW operation

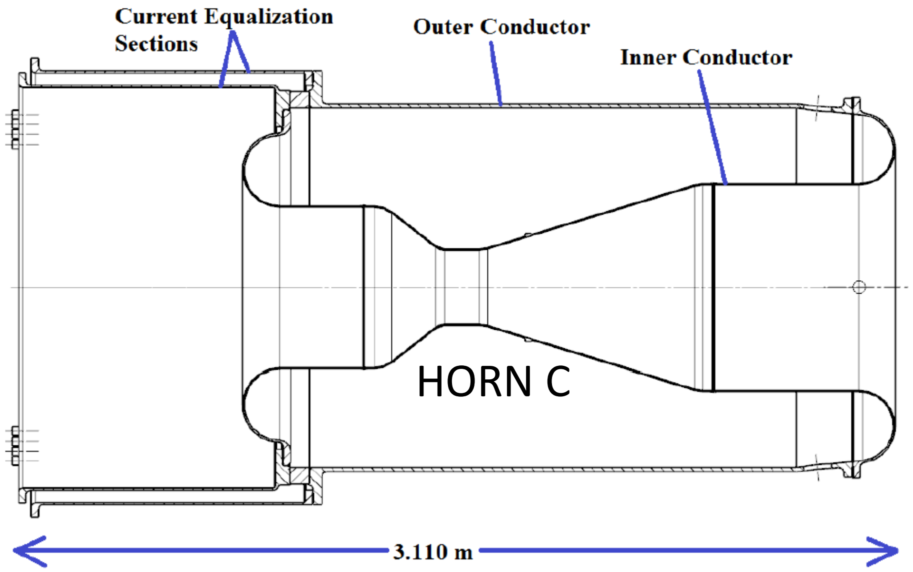


NuMI & Nova utilize a parabolic conductor shape

Optimized horn designs use a combination of cylindrical and conical profiles

Optimized horns designed to produce a neutrino beam with energy spectrum appropriate for physics goals of LBNF/DUNE



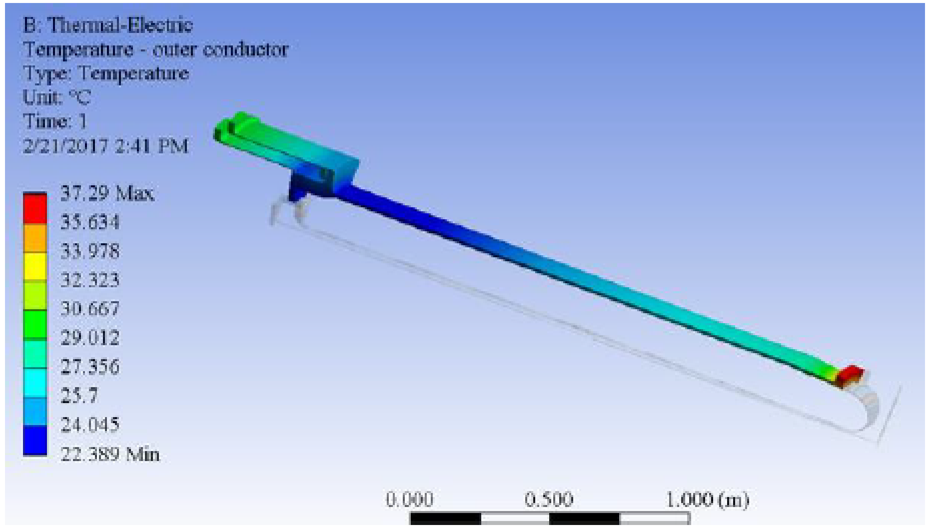


Have completed conceptual design of optimized horns

Temperature and Stress looks OK

FEA of Horn A, which has highest current density and beam heating

- Horn must endure stress due to combined heat load of beam heating and Joule heating
- Horn A is the critical horn for operational stress and expected service life
- CFD has shown that the water cooled horn operating temperature is well within acceptable limits (max 40°C)
- FEA of the magnetic forces and thermal stresses indicates reasonable safety factors on stress.



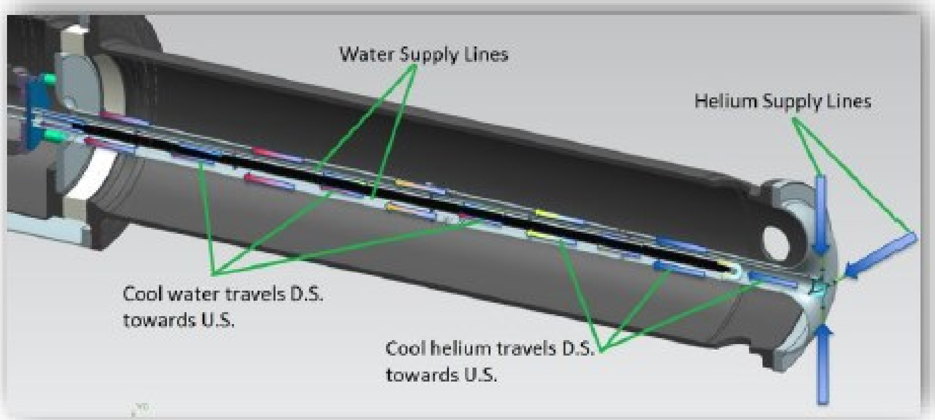
	Safety Factor for stress	
Point	No preload	With Preload
1	1.87	2.00
2	1.36	1.75
3	2.2	3.00
4	2.46	3.10
5	1.91	2.10
6	1.91	2.10

Cory Crowley

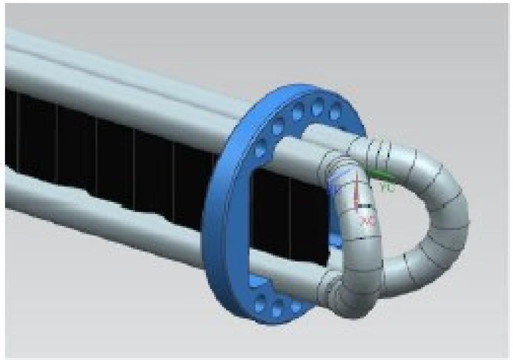
Target Alternatives for 1.2MW beam

Iteration 1 (NuMI style)

water cooled graphite fins



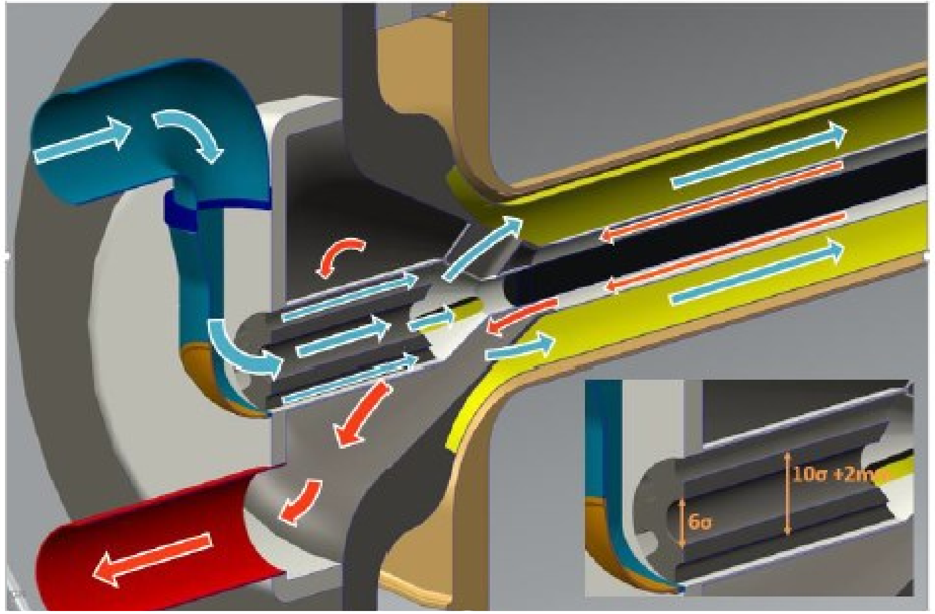
Graphite fins brazed to Titanium tubes carrying water



Down Stream Cooling Loop Transition (Turn Around)

Iteration 2 (RAL Design)

Graphite cylinders centred in coaxial titanium carrying helium



Advantages of Iteration 2

No pressure pulse and vibration associated with sudden water heating

Graphite at significantly higher temperature - radiation damage

partially annealed.

Larger beam spot, lower pulsed power density

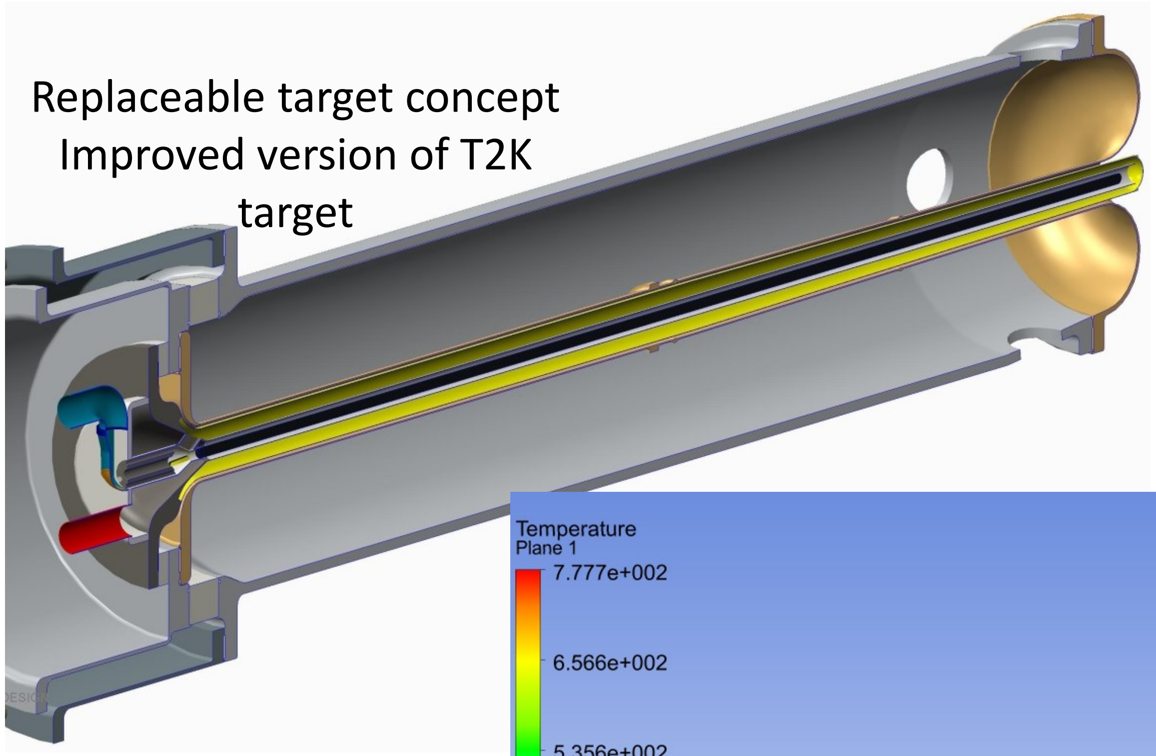
Target designed to be removable from horn and replaceable

Targets and horns may last longer!

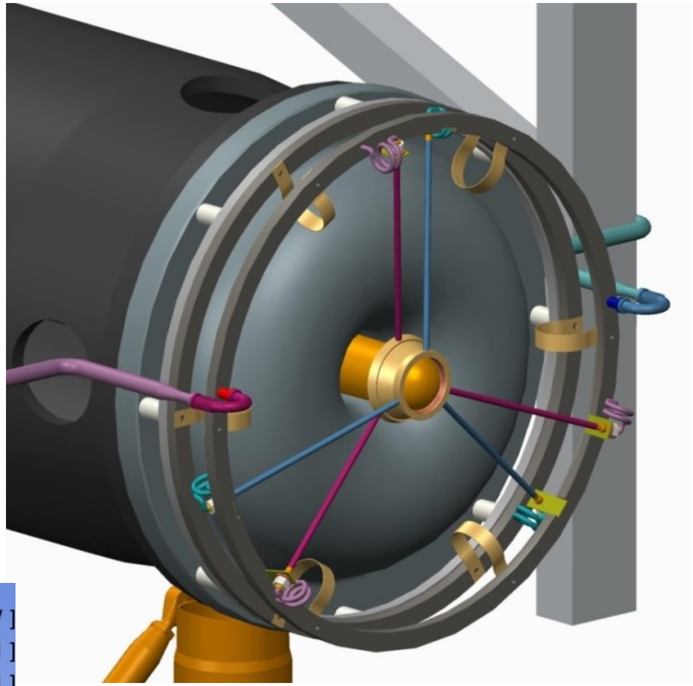
Jim Hylen

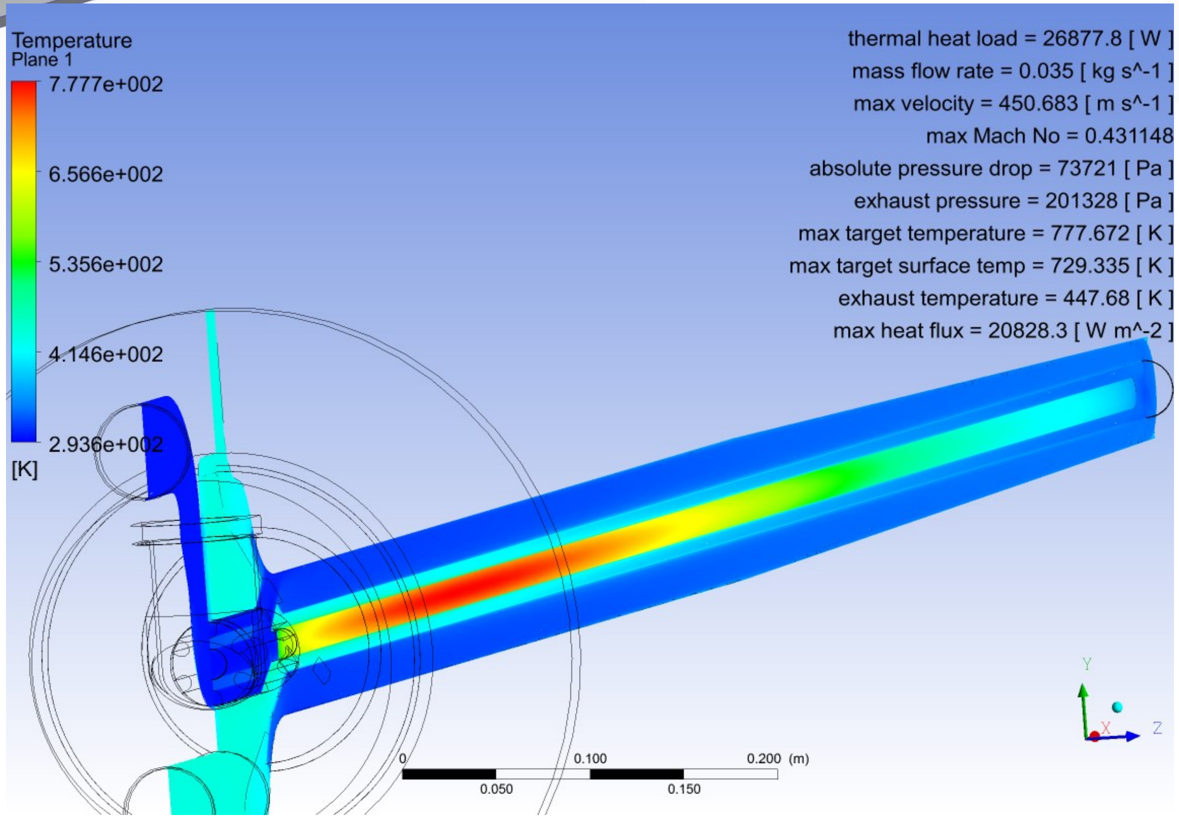
RAL 1.2MW outline target design completed

Replaceable target concept
Improved version of T2K target



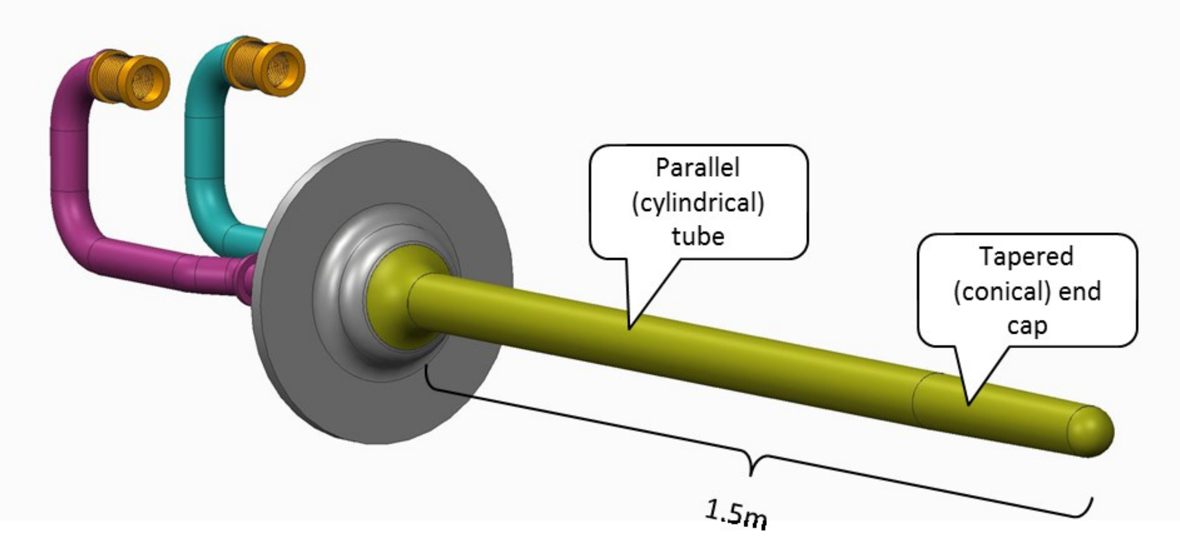
2m+ target must remotely dock into a cooled downstream support

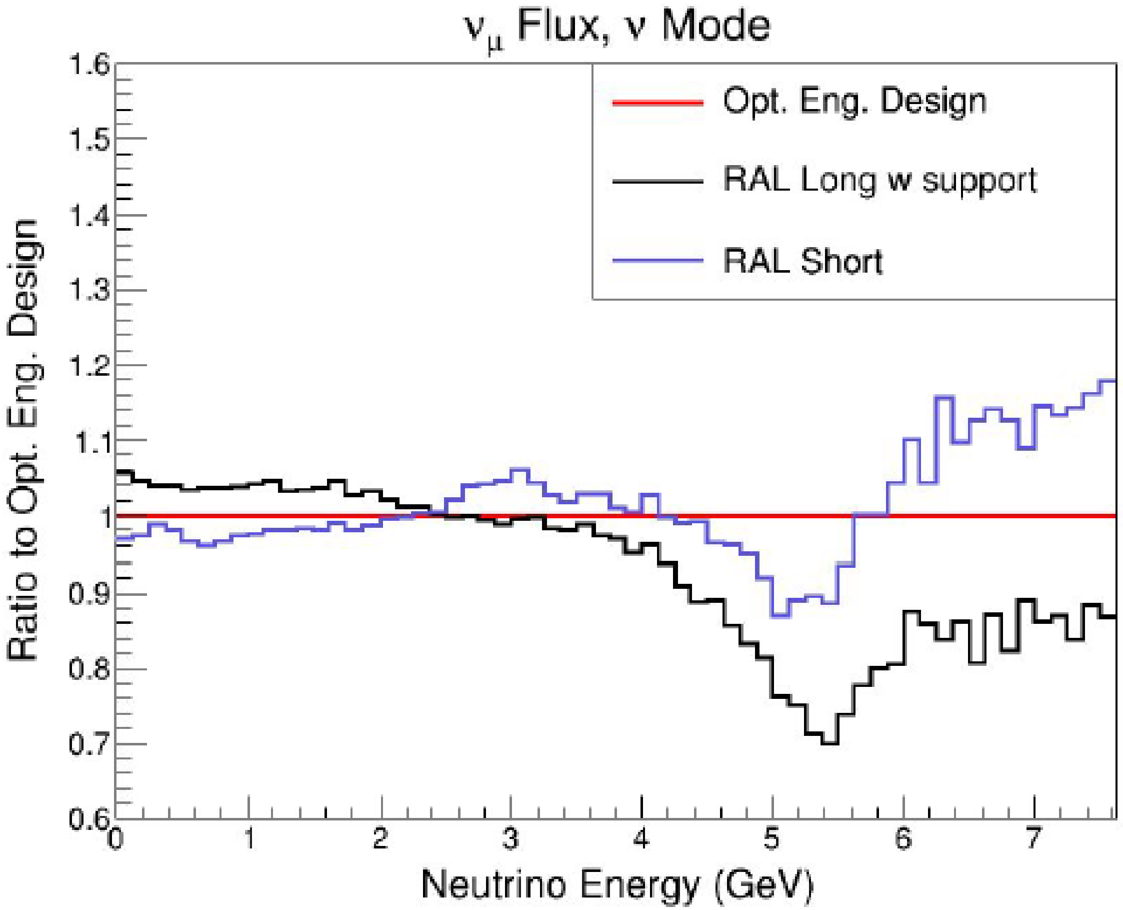




CFD and FEA indicate that with 28kW heat load and 35g/s of helium operating temperature, pressure and stress OK

Risk Mitigation

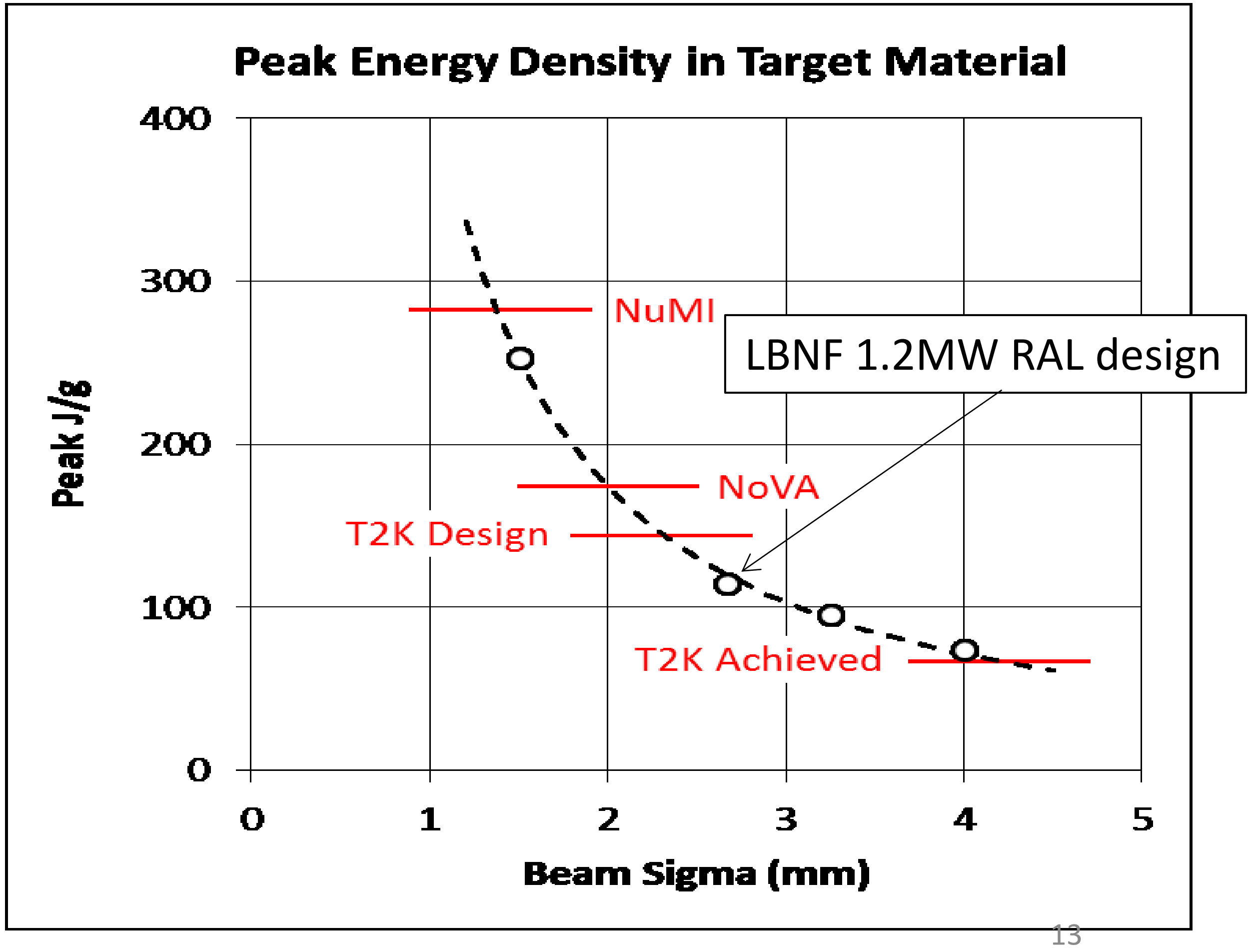




- A 1.5m long target can be cantilevered
- No downstream support required
- Easier to manufacture
- Tolerable penalty on physics yield?

Target loading comparison

	T2K (Designed For)	T2K (Achieved)	NuMI	NoVA	LBNF RAL Design
Target Material	ToyoTanso IG-43	ToyoTanso IG-43	POCO ZXF-5Q	POCO ZXF-5Q	ToyoTanso IG-43
Beam Energy [GeV]	30	30	120	120	120
Beam Power [kW]	750	350	400	700	1200
Beam Current [μA]	25	12	3.3	5.8	10
Protons per Pulse	3.3×10^{14}	1.8×10^{14}	4.0×10^{13}	4.9×10^{13}	7.5×10^{13}
Cycle Time [s]	2.1	2.5	1.9	1.3	1.2
Beam Sigma [mm]	4.2	4.2	1	1.3	2.7
Peak Energy Density in target material [J/g]	144	67	282	174	118
Peak Proton Fluence on Front Face [μA/cm²]	23	11	53	55	22



Energy & radiation deposition

- Much of work for design of high power neutrino beam is radiation and rad safety
  - Prompt, air-borne, ground-water, residual, remote handling, radiation damage, …

Let's start by looking at where the beam power ends up.

System	RD (kW)	OD (kW)	OD/RD
Target Pile	952	1238	1.30
Decay Pipe Region	452	542	1.20
Hadron Absorber	786	400	0.51
Misc: infrastructure, binding energy, sub-thrshld	144	151	1.05
Neutrino power	66	69	1.05
Total	**2400**	**2400**	

For 2.4 MW proton beam power

← kW deposited in region

For Ref. Design (RD) and Opt. Design (OD)

~ 10^{-13} watt deposited in far detector !

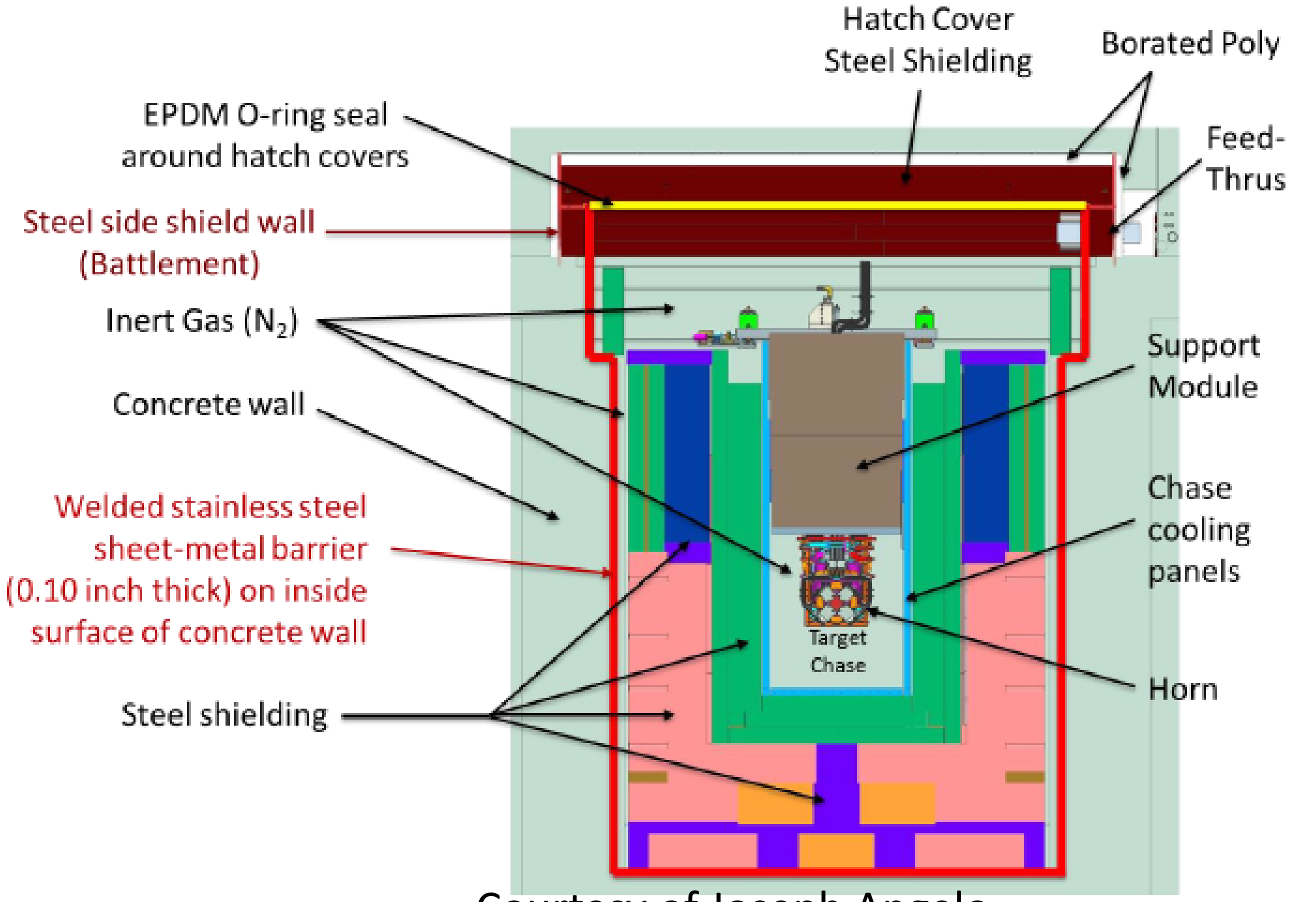
MARS Monte Carlo

Jim Hylen

Cooling design choices

LBNF designed for 30 year lifetime. All water piping required to be replaceable/repairable.
→ Use gas cooling for permanent/unreachable structures.

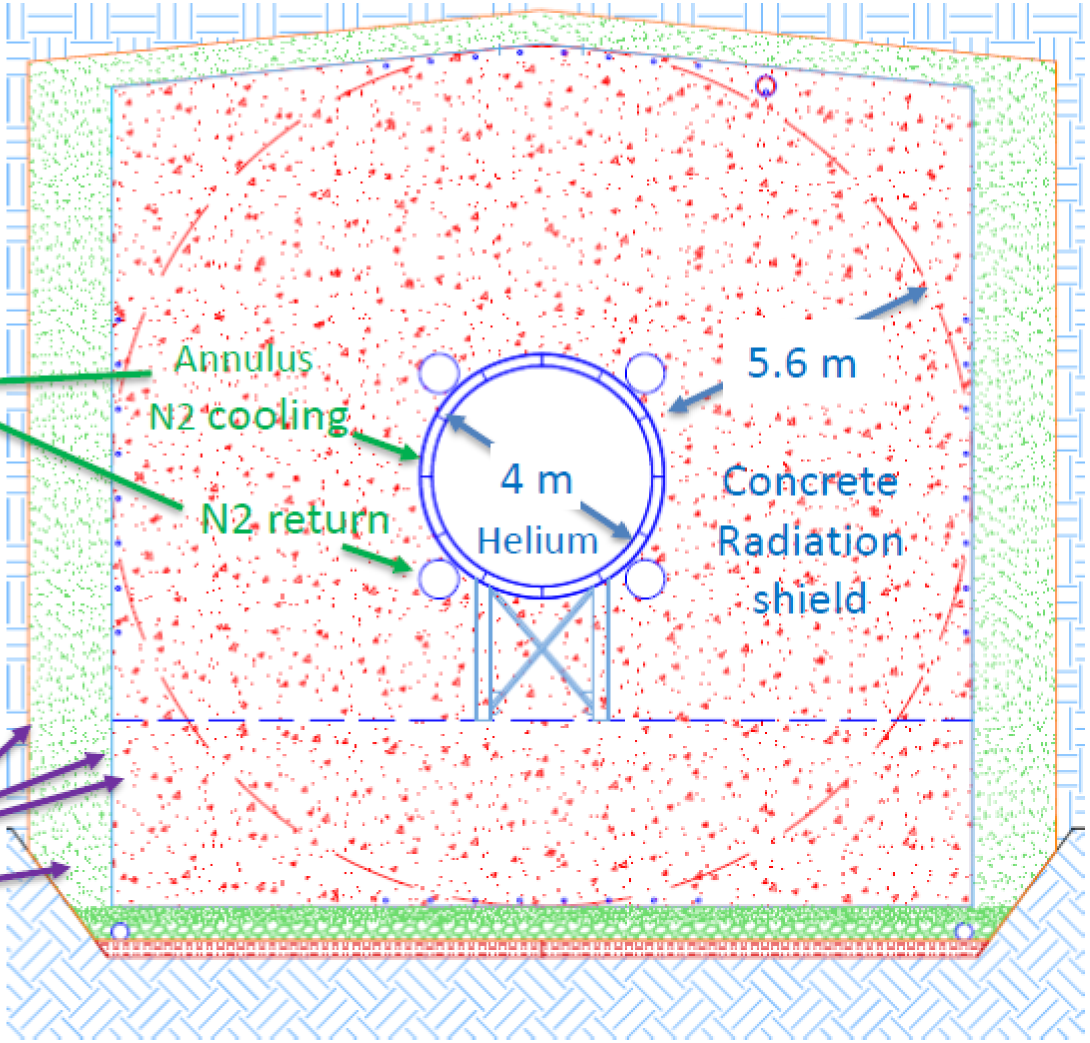
- Water cooling panels used for innermost steel layer
- N_2 atmosphere instead of air due to production of 41Ar, ozone and nitric acid
- Bulk shielding cooled by 35000 CFM of N_2
- Continuously purge tritium with slow release of N_2 (1 to 7 CFM)



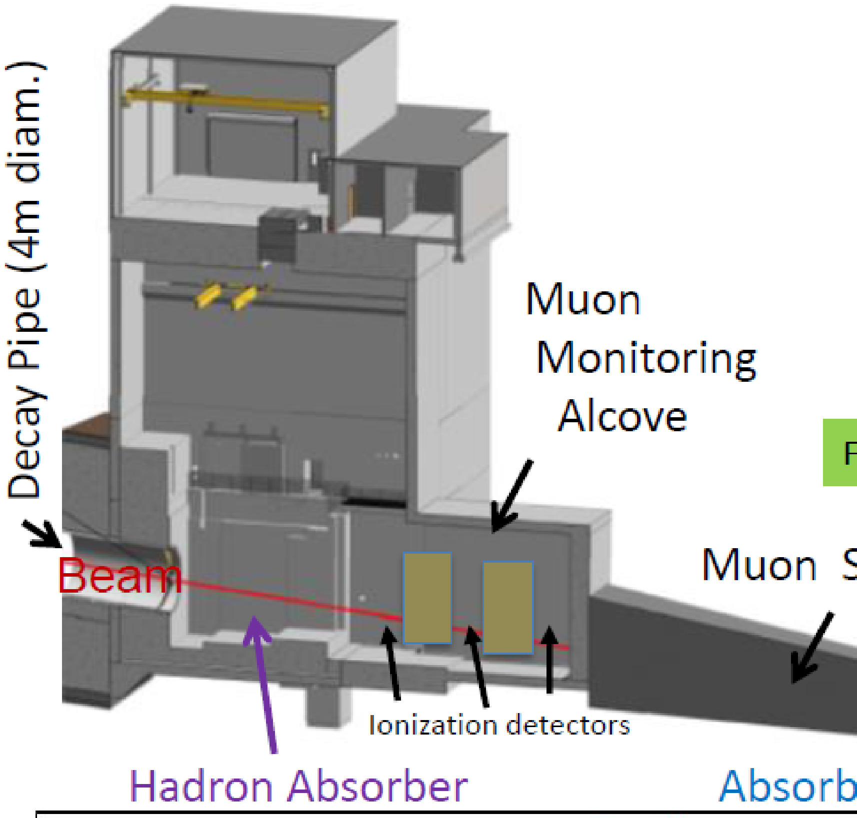
Courtesy of Joseph Angelo

Decay pipe region

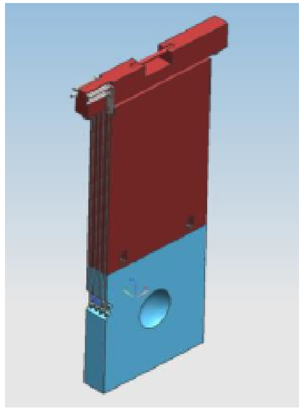
- Decay pipe is 4m diameter and 194m long
- Pipe filled with helium as this allows 10% more neutrinos as compared to filling with air
- Cooled by 35000 CFM of N_2
- Structure dominated by concrete radiation shielding
- Multiple features to keep water out



Absorber region

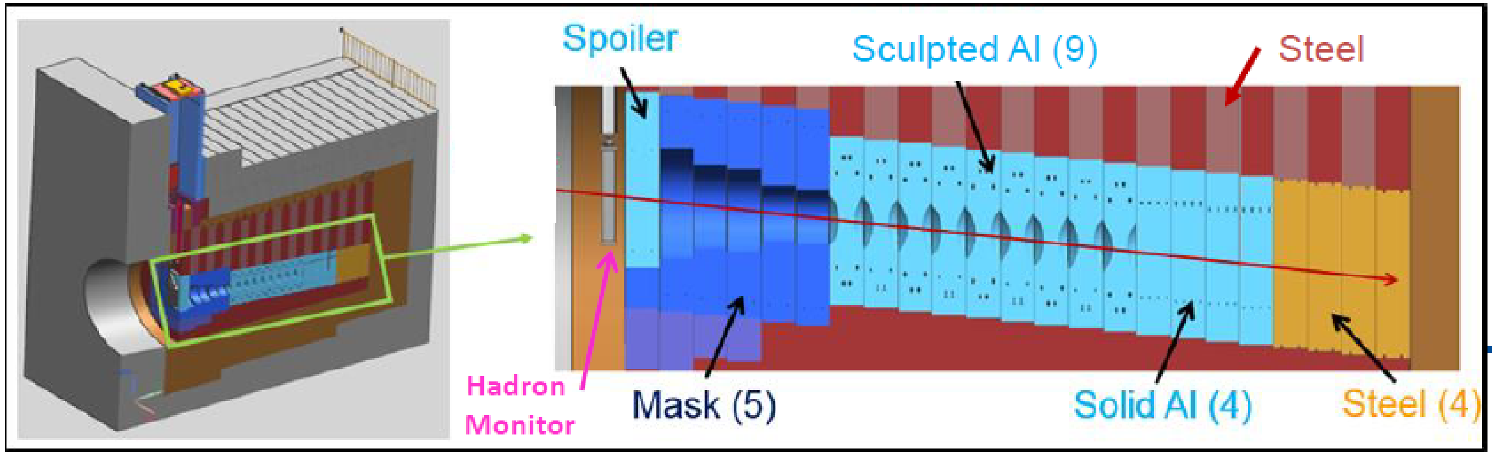


Core blocks are replaceable via Remote Handling (each 1 ft thick)



Flexible, modular design

- Energy deposition significantly less for optimised beam
- Optimised beam may allow for widening mask holes and elimination of sculpting of core blocks which would be beneficial for muon monitoring capability



Core:
water-cooled

Rest of shielding:
forced air-cooled

Summary

	2015 Reference design	2017 optimised design for DUNE physics
Beam Focusing	NuMI 2-horn system	3-horn system with longer target gives significantly improved physics performance, 2 horn staged option also on the table
Target	NuMI target, 1m long water cooled graphite fin target	Iteration 1 - 2m long 1.2MW version of NuMI target. Iteration 2 - 2m long Helium cooled graphite target Higher temperature operation No water hammer Target replaceable without replacing horn
Target pile	Air atmosphere	N_2 atmosphere to deal with 41Ar. Also reduces ozone and nitric acid corrosion issues
Absorber	Complex sculpted absorber plates	Lower power absorption allows simpler design which also facilitates better muon monitoring

Decision on which approach to take to be made imminently (end of 2017)

First beam to DUNE about 2026, power up to 2.4MW in about 2032