Design of the LBNF Beamline

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LBNF = Long Baseline Neutrino Facility

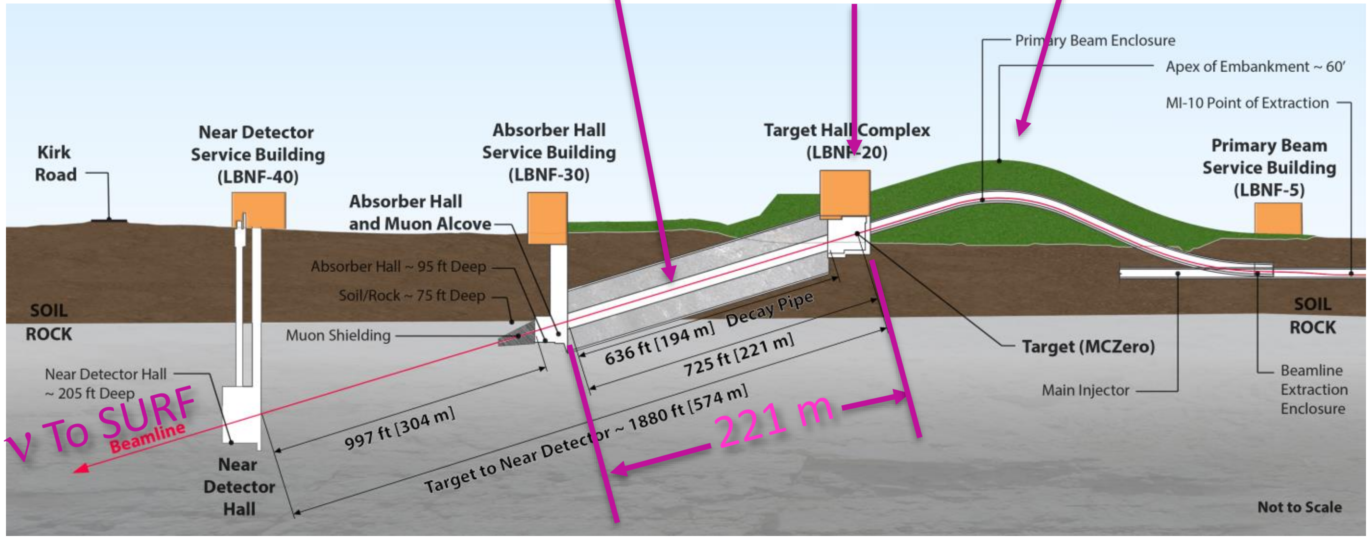
Takes protons from Fermilab accelerator

Produces beam of ν_μ or $\bar{\nu}_\mu$

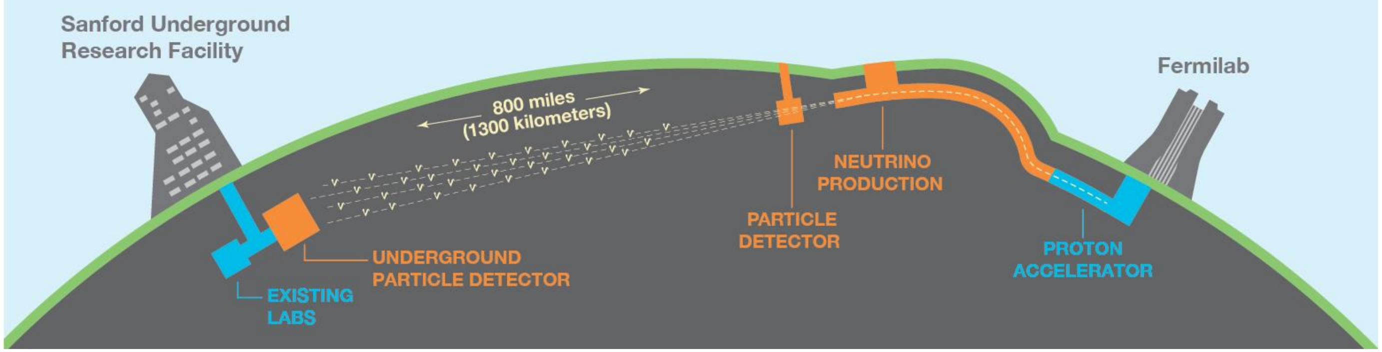
$\pi \rightarrow \nu$ decay

Target & Horn Focusing

Protons (tunable 60 GeV to 120 GeV)



Aimed at DUNE detector in SURF 1300 km away

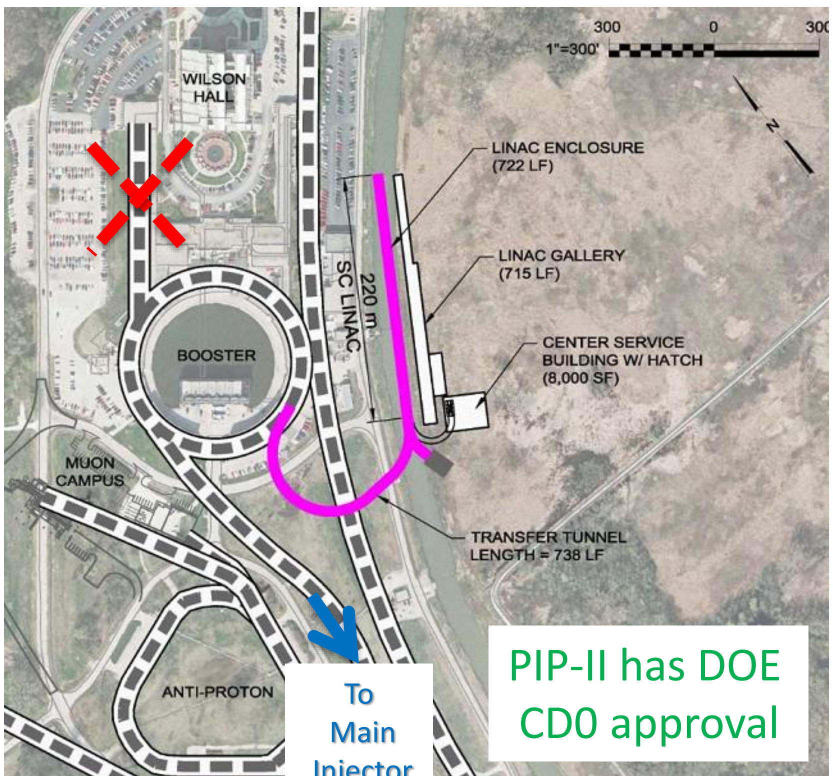


Study neutrino oscillation phenomena

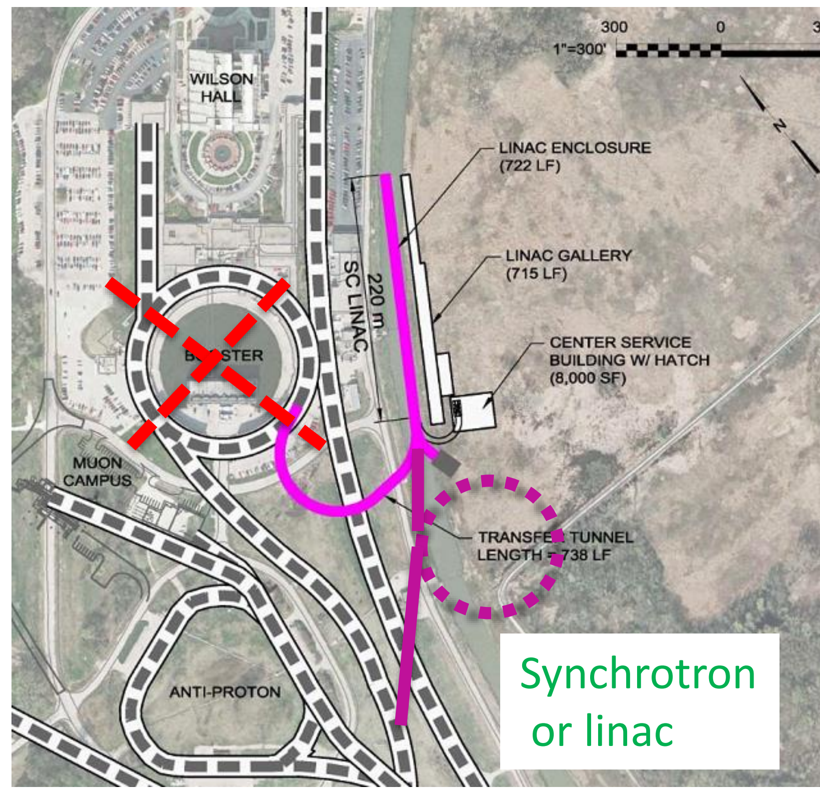
Accelerator stages: Linac -> Booster -> Main Injector -> *beamline*

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

Detector drivers for LBNF beam design

- Detector to measure CP violation; $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - Beam should produce as many neutrinos as possible around 1st and 2nd oscillation peaks (E_ν ~ 2.4 and 0.8 GeV for L=1300 km)

- Does 3-ν mixing picture hold together ?
  - Broad energy spectrum to look for deviations as function of L/E
  - Implies beam pointed at detector, rather than off-axis (T2K and NOVA)

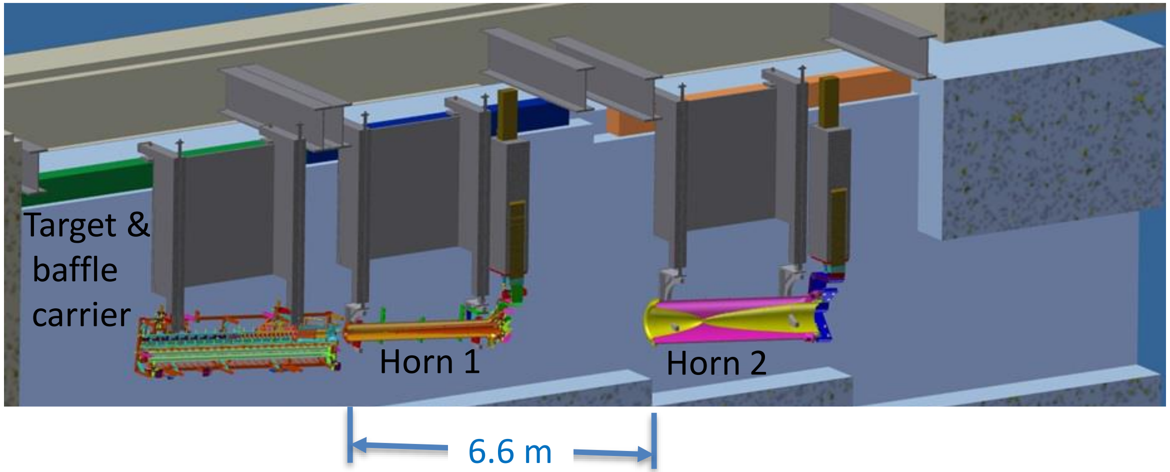
- DUNE far detector is non-magnetized
  - ν vs $\bar{\nu}$ selection done by beam focusing π^+ or π^- (defocus other)
  - Toroidal horn magnetic field, (rather than e.g. solenoid-gradient focusing)

- Detector and beam will run for decades
  - Include flexibility to modify beam-line, e.g. for higher E_ν spectrum
  - Implies possibly different target/horn shapes and locations

Two different horn configurations on table, *plus staging options*

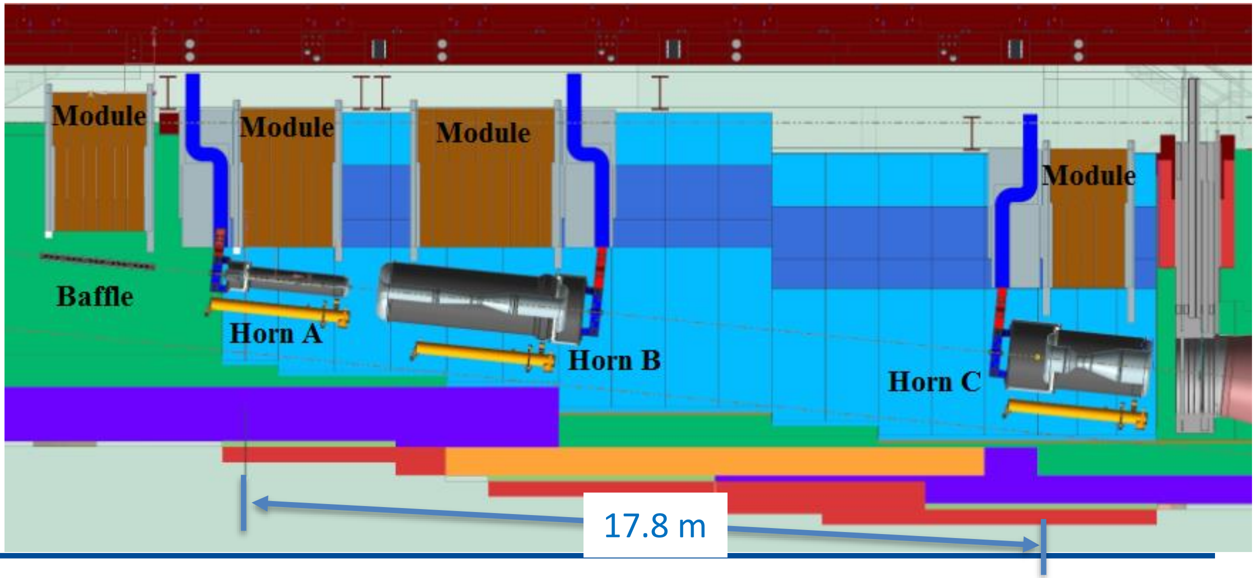
CD-1 Reference lower-cost starter, based on proven NUMI tech, …upgraded/replaced later

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



Optimized design recent optimized configuration for DUNE CP violation

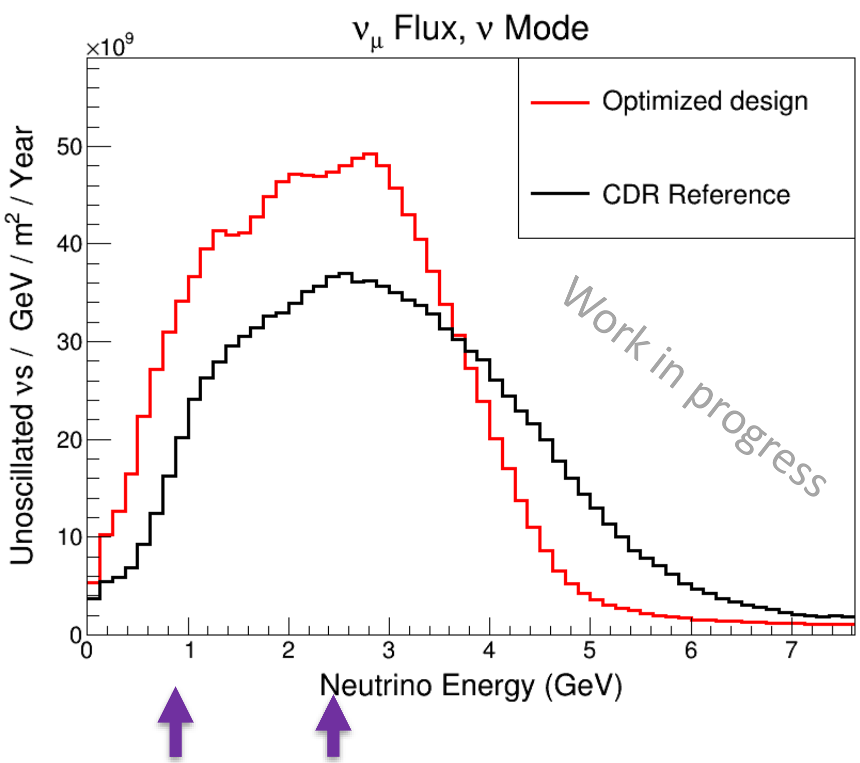
- 3 horns
- 2 m long target
- Target mounted entirely in horn A



Optimized staged

- start with just 2 of the 3 optimized horns

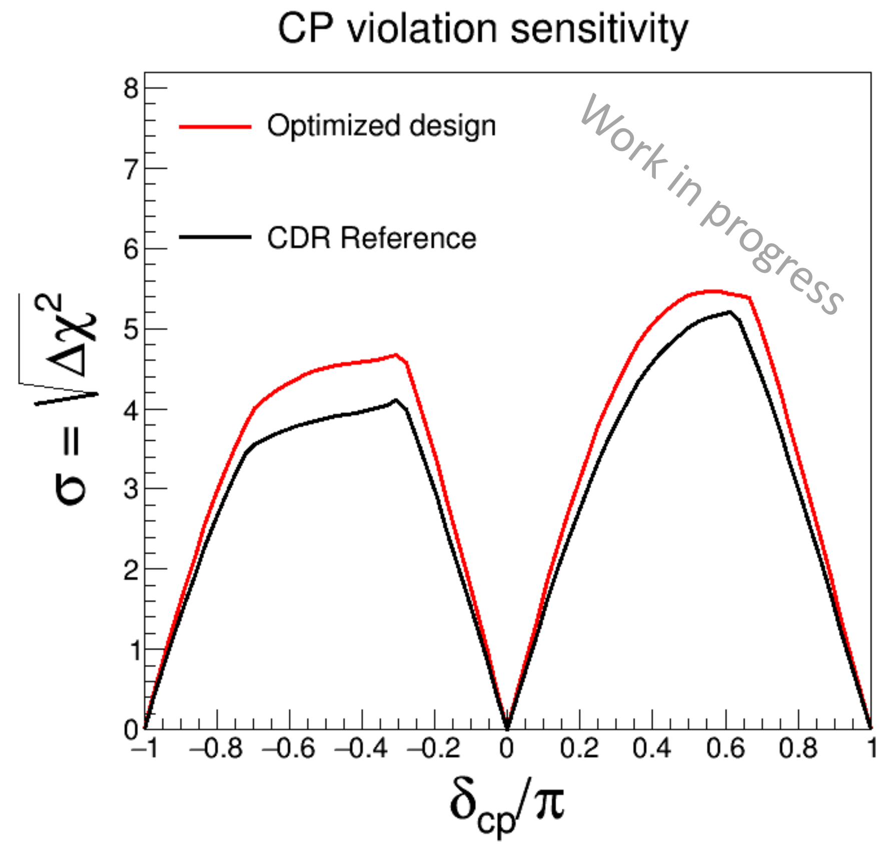
Optimized versus reference design



2nd and 1st oscillation max.

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

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



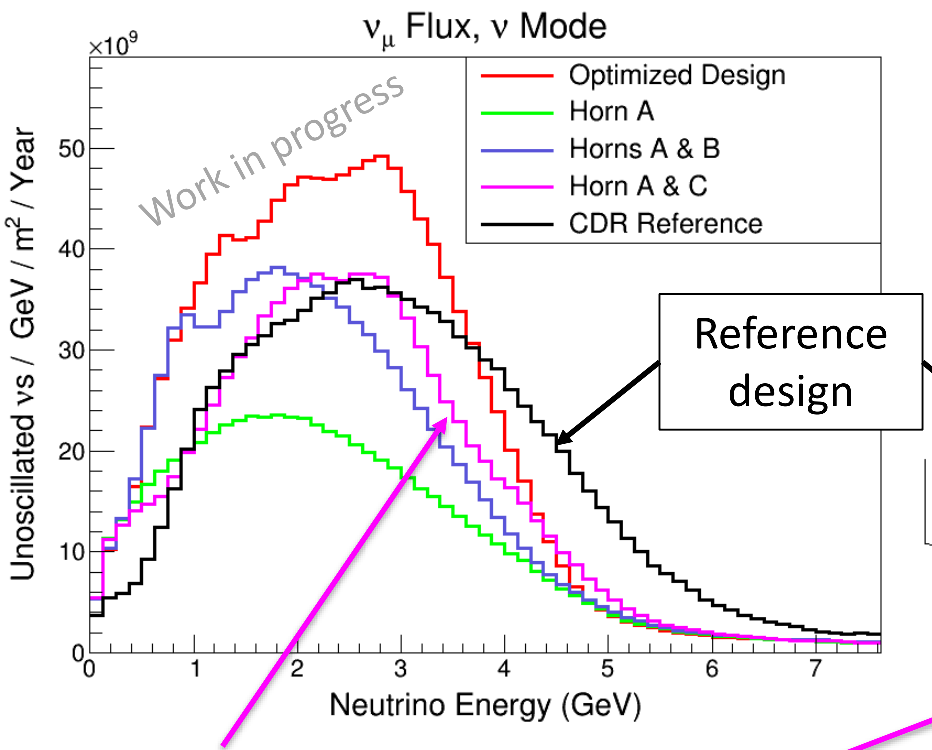
Optimized system:

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

See Rowan Zaki's presentation "Optimization of the LBNF Neutrino Beam"

Beam-line Staging possibility

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



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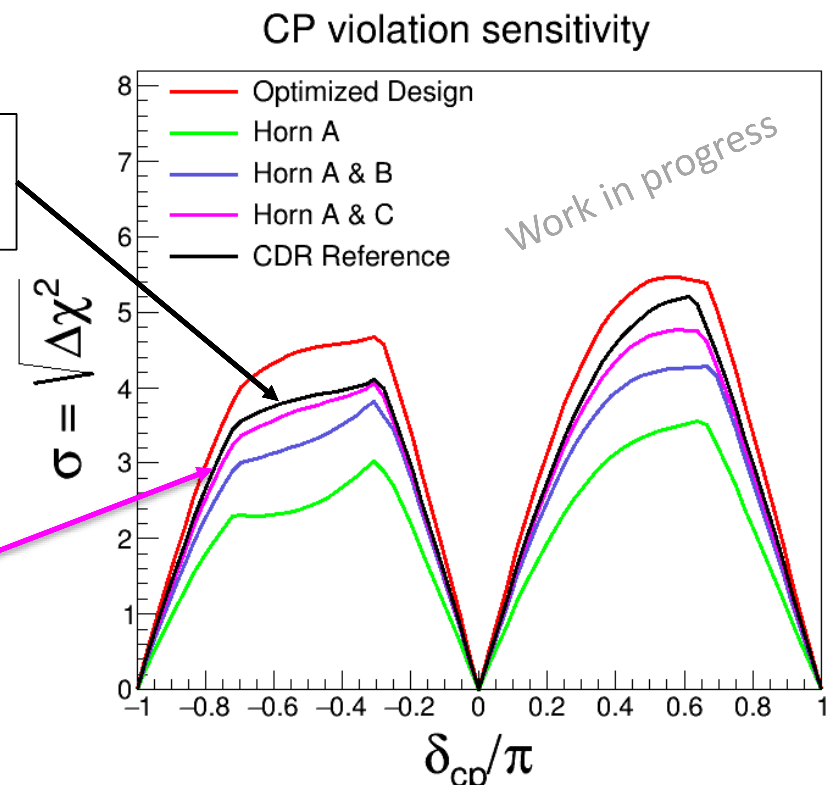

Using horns A&C from optimized design is nearly as good as the 2-horn reference design

- would allow much easier later upgrade to fully optimized

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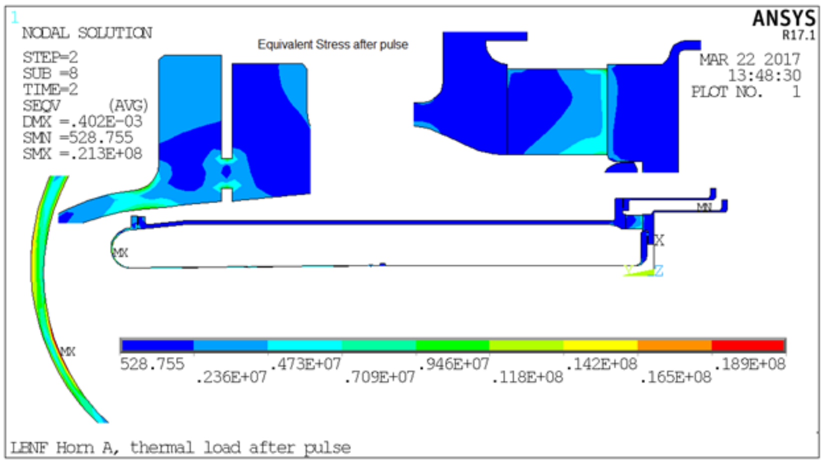
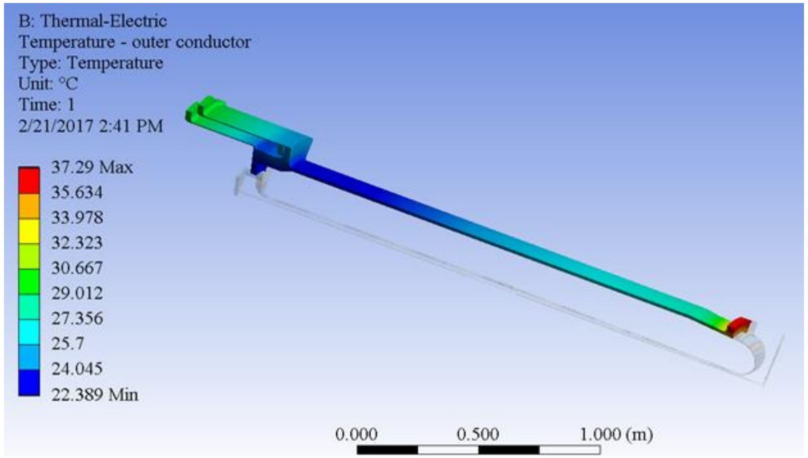
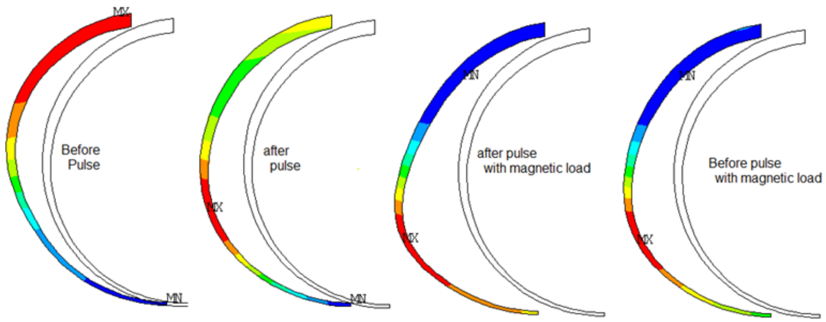
Have completed conceptual design of optimized horns

Temperature and Stress looks OK

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







	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

See further information in Cory Crowley's poster
"LBNF Optimized Horn Design & Target Integration"

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**	

MARS Monte Carlo

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 !

Target pile *inside* target hall

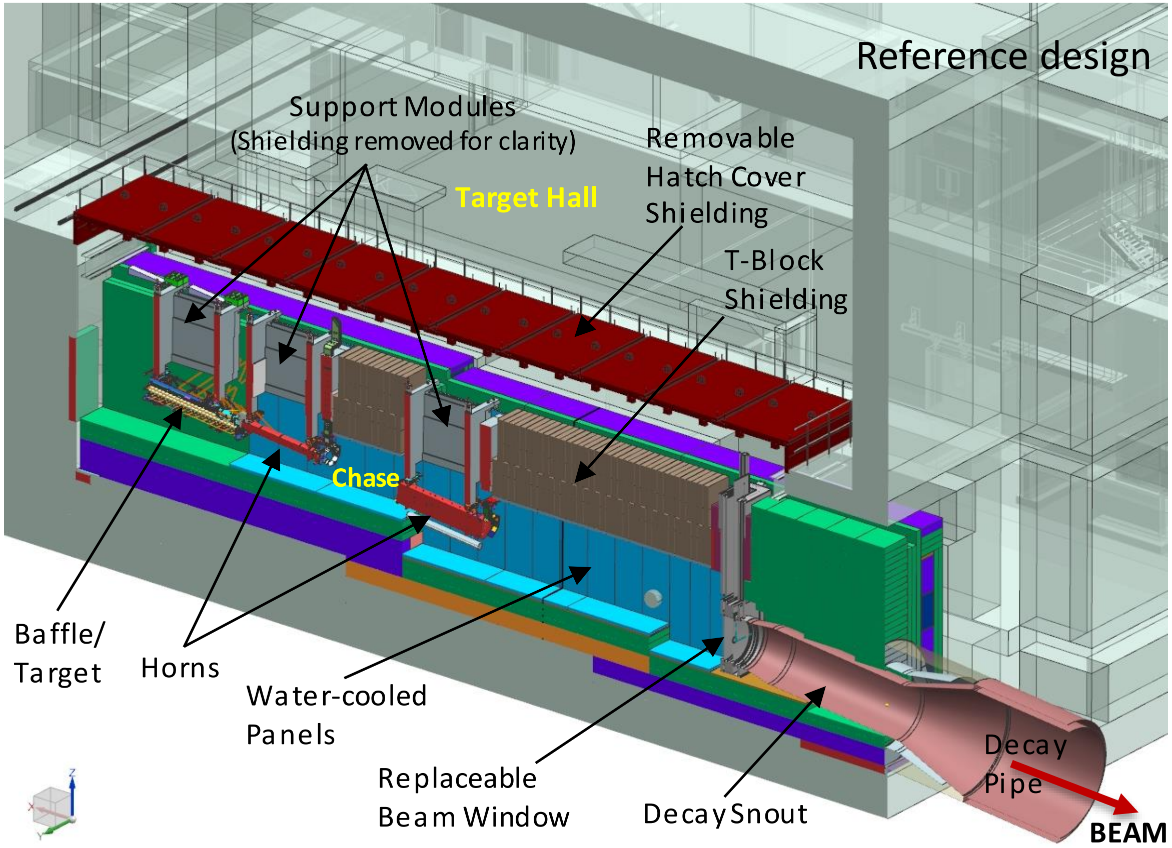
- Radiation shielding around target:
  - 1.8 m steel + 1 m concrete thick on sides
  - 3 m steel + 15 cm Borated Poly on top

Recent work:
Changed gas in pile from air to N_2;
eliminates ^{41}Ar production,
also ozone + nitric acid corrosion

- Component alignment:
  < 1 mm

- (nearly) sealed gas volume

- Target & horn handling
  all remotely done due to
  high residual radiation



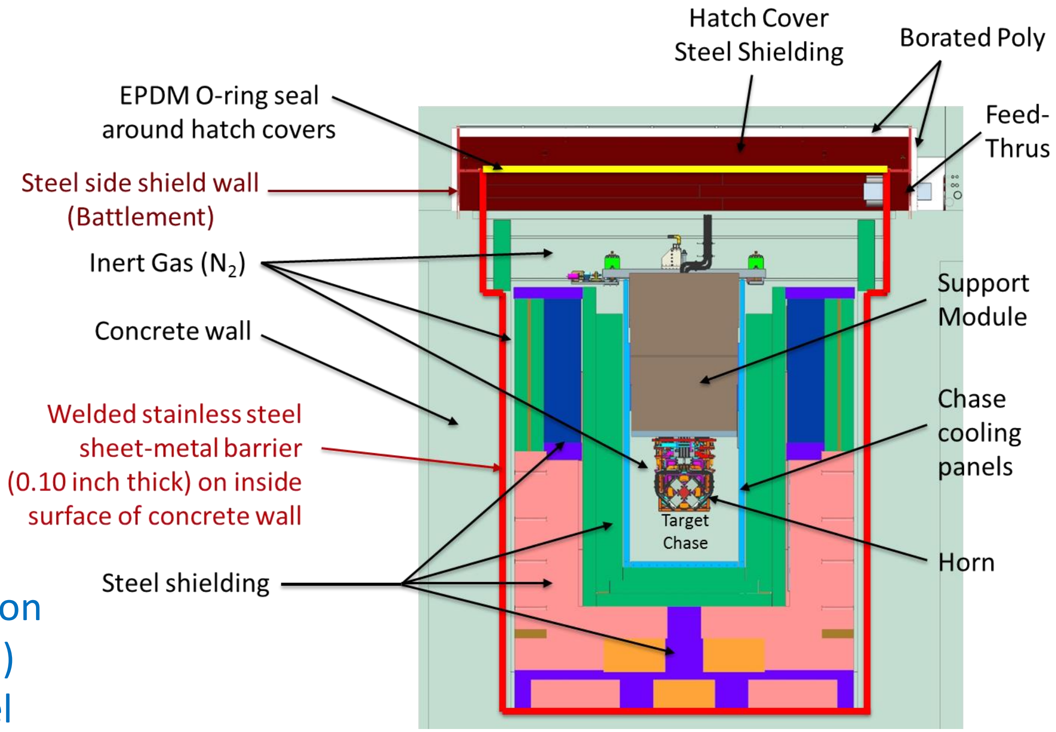
Cooling design choices

LBNF designed for 30 year lifetime. All water piping required to be replaceable/repairable.

→ Use gas cooling for permanent/unreachable structures.

Replaceable water cooling panels are used for innermost steel layer

Bulk shielding is all cooled by 35,000 ft^3/minute flow of N_2 gas



<u>Lessons learned being applied:</u>

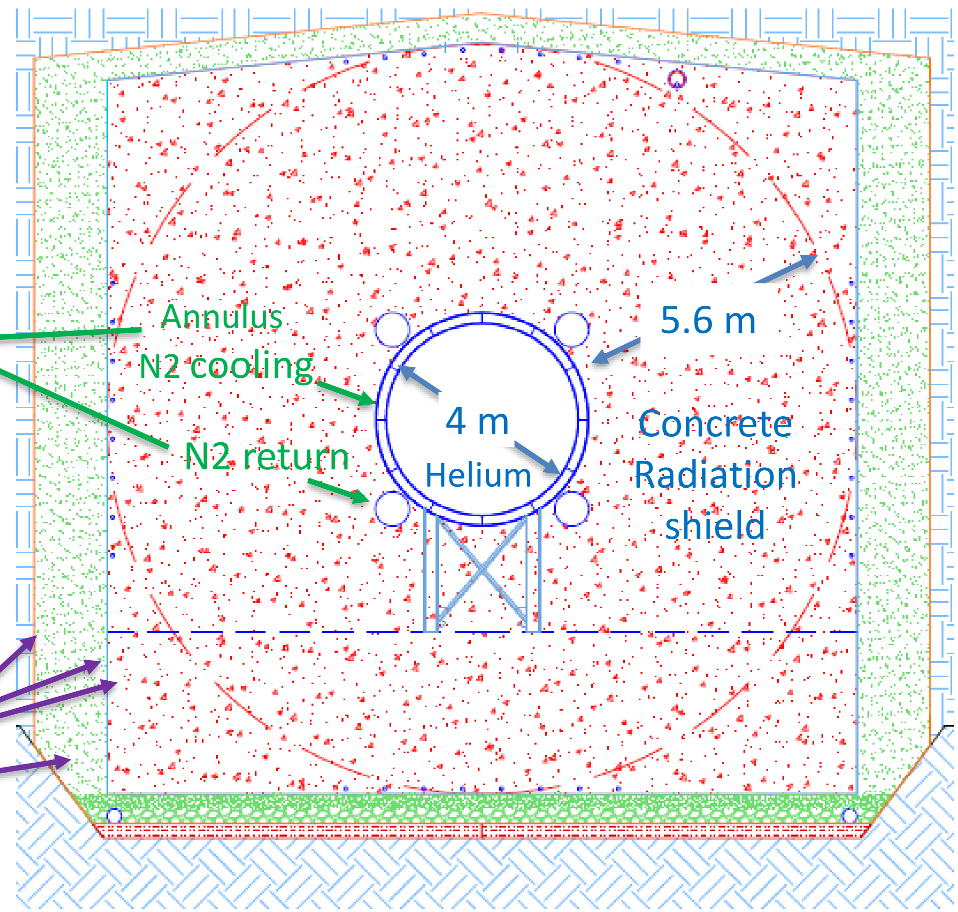
- Concrete is all outside the N_2 vessel
- Vessel includes all gas in high radiation (containing short-lived air-activation)
- Steel (emitting tritium) is all in vessel
- Continuously purge tritium by slow N_2 release (1 to 7 cfm)

See Joseph Angelo's poster
"Design of a Nitrogen Cooled Target Shield Pile for the LBNF Beamline"

Decay pipe region

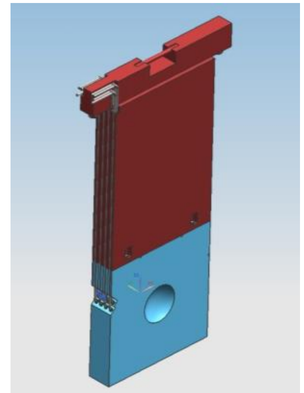
Recent work:
Changed gas cooling from air to N_2,
reduces ^{41}Ar production, also corrosion

- Pipe is 4 m diam., 194 m long
- Static helium fill
(10% more ν compared to air fill)
- Cooled by flowing 35,000 ft^3/minute of nitrogen gas
- Structure dominated by concrete radiation shield
- Multiple features to keep water out

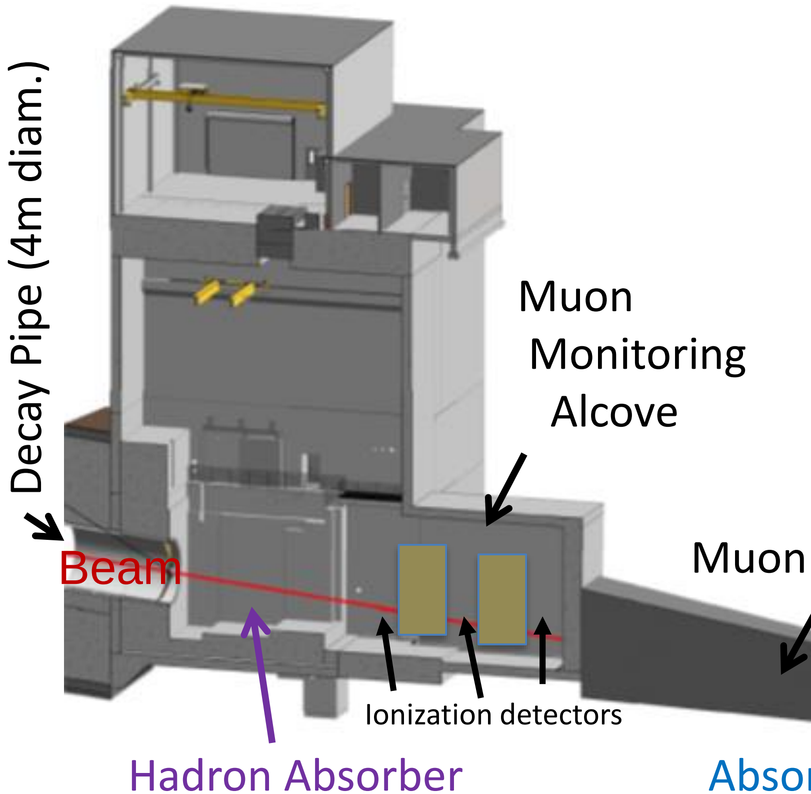


Absorber region

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



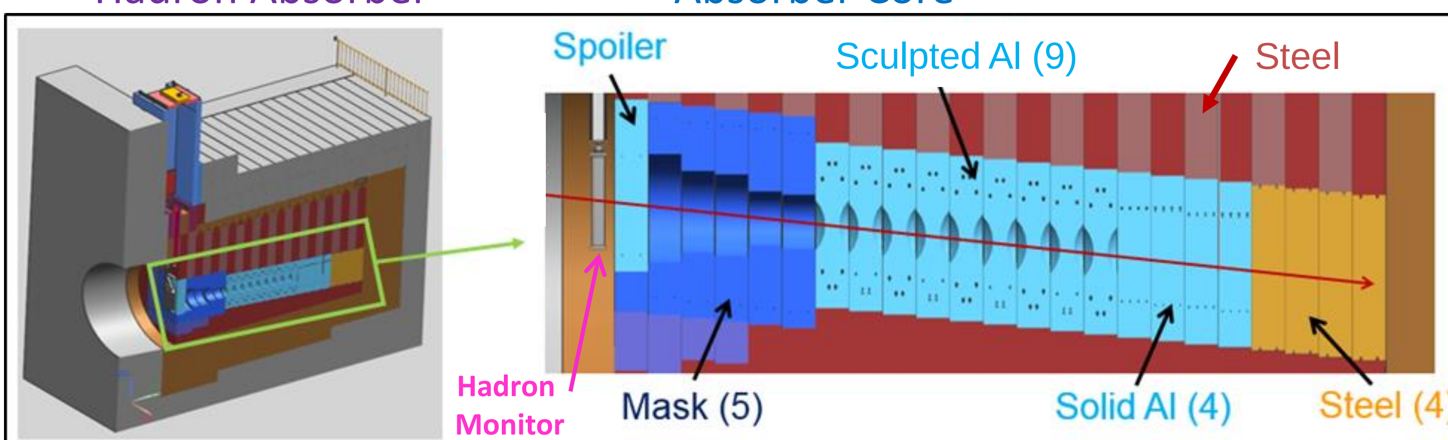
Flexible, modular design



Recent work:

Energy deposition is *LESS* for opt. beam than for ref. beam

Opt. beam may allow widening mask holes & elimination of sculpting of core blocks, *thus improving muon monitoring capability*

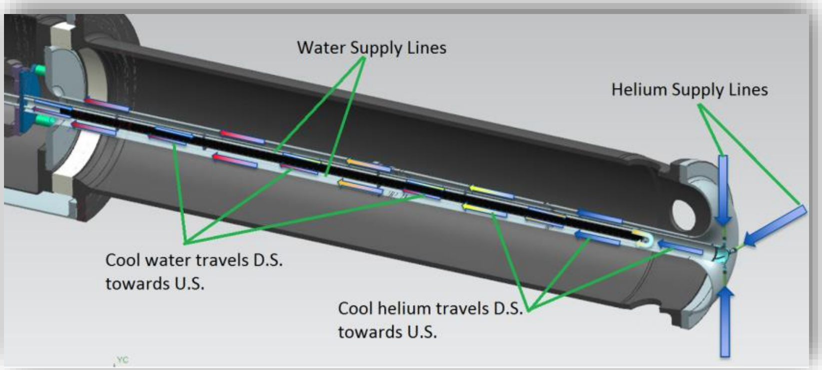


Core: water-cooled

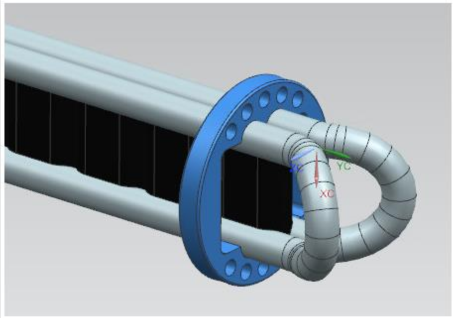
Rest of shielding: forced air-cooled

Target alternatives for opt. beam: both 2 m long graphite

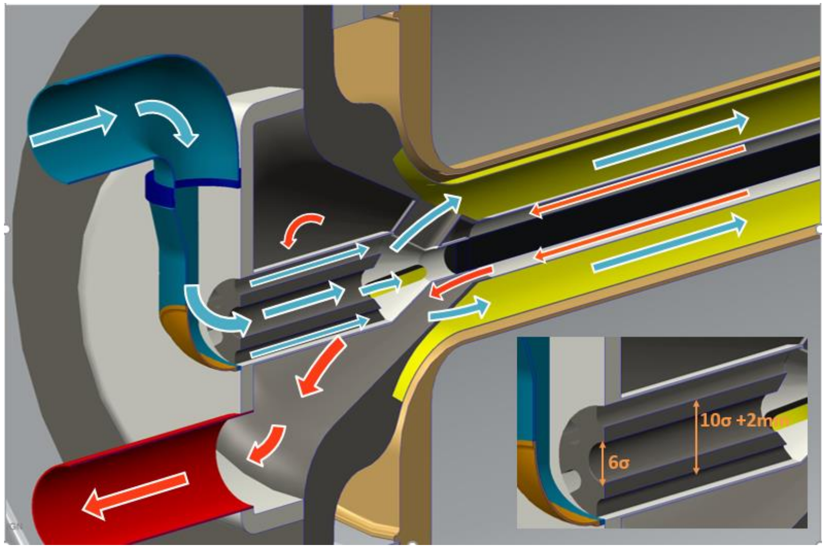
- Existing design (NuMI-like)
  - Water-cooled
- Being developed by RAL-UK
  - Helium-cooled



Graphite fins brazed to Titanium tubes carrying water



Down Stream Cooling Loop Transition (Turn Around)



Graphite cylinders centered in coaxial Titanium tubes carrying helium

Graphite at significantly higher temperature;
Radiation damage partially anneals at high T
Target may last longer !

Summary: Continue to make progress on LBNF beam design

<u>Beam focusing:</u>

- Have complete reference conceptual design for a NuMI-like 2-horn system
- Nearing completion of conceptual design for a 3-horn system with longer target, **optimized for DUNE detection of ν CP violation**. This system also allows an attractive 2-horn staging scenario.

Plan to make decision in the fall of 2017 on which course to pursue through preliminary design.

<u>Target pile atmosphere and decay pipe cooling:</u>

- Completed conceptual design for replacing air fill with nitrogen
  - Eliminates production of radioactive ^{41}Ar
  - Eliminates Ozone and Nitric Acid corrosion

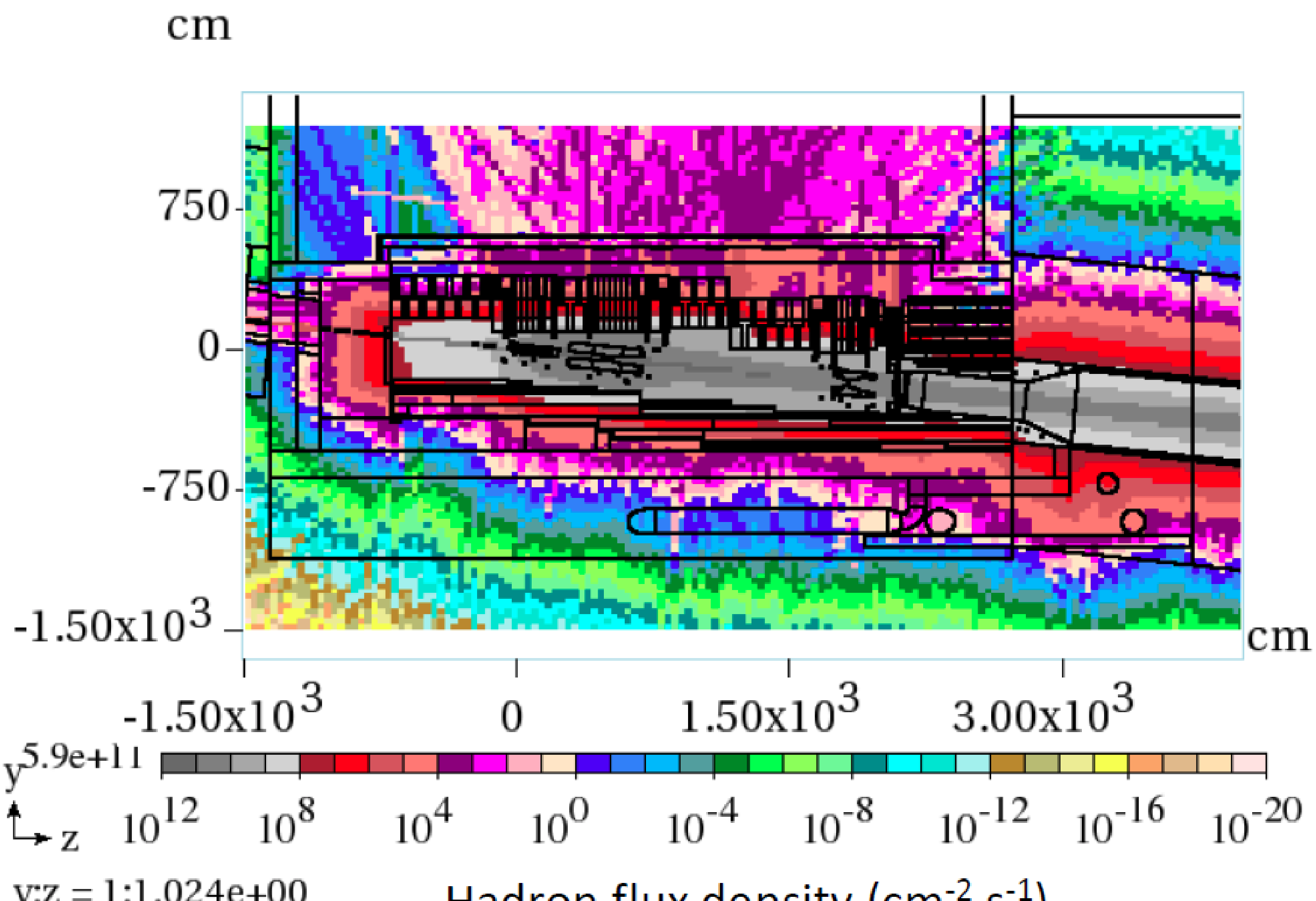
<u>Target</u>

- Developing Helium cooled target design, alternate to reference water cooled design

Beam to DUNE about a decade from now

BACK-UP

Hadron flux for calculating air activation in target pile



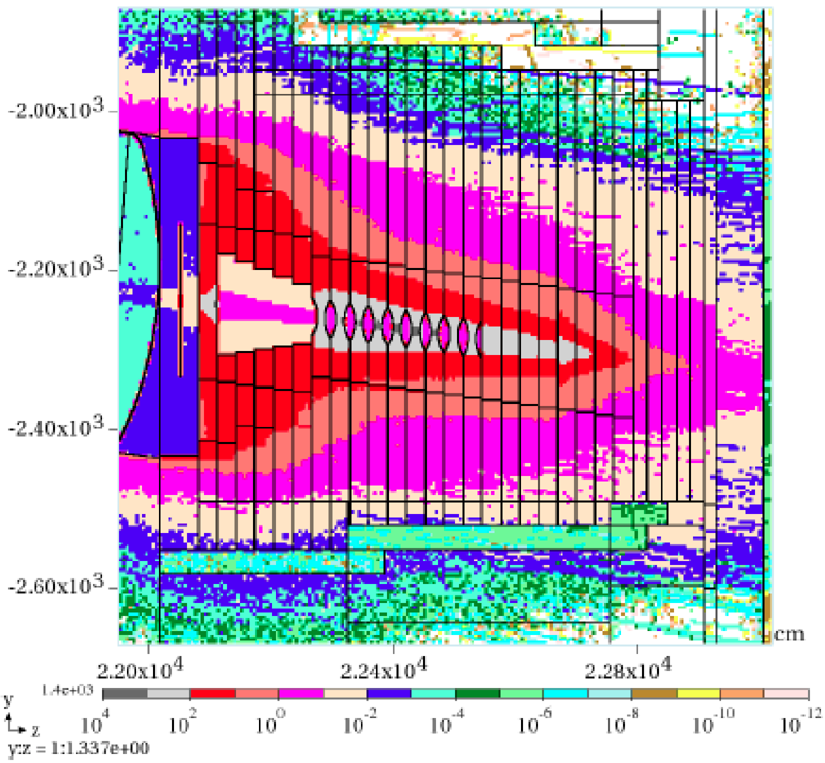
Hadron flux density (cm^{-2} s^{-1})

For Hadrons > 30 MeV

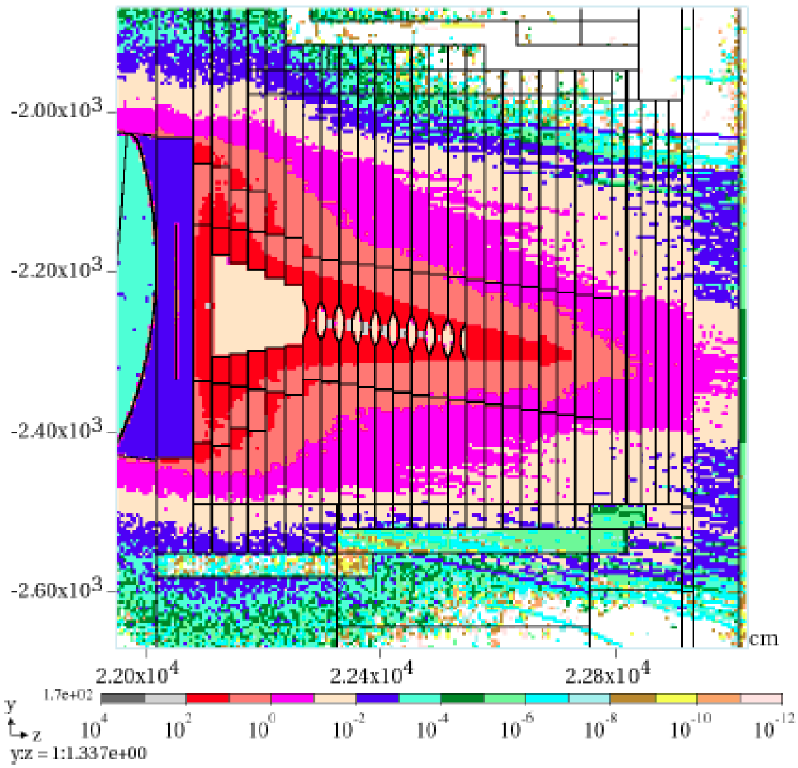
MARS Monte Carlo

Power Density (mW/cm^3) in Hadron Absorber

RD Peak: 1.6 W/cm^3



OD Peak: 0.24 W/cm^3



MARS Monte Carlo