The Science and Design of the LBNF Beamline

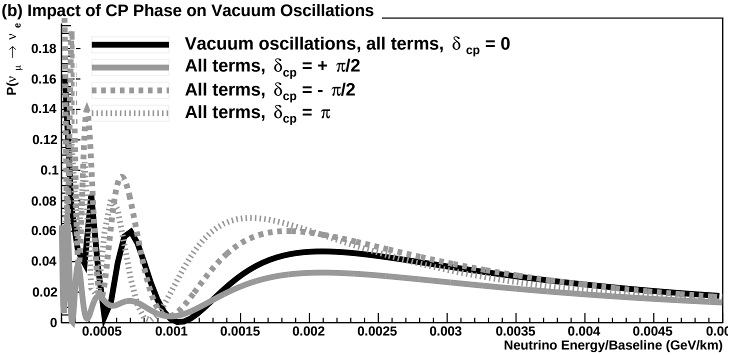
NuFact 2018, Aug 12-18, 2018, Blacksburg, VA

Mary Bishai (on behalf of LBNF/DUNE)
Brookhaven National Lab

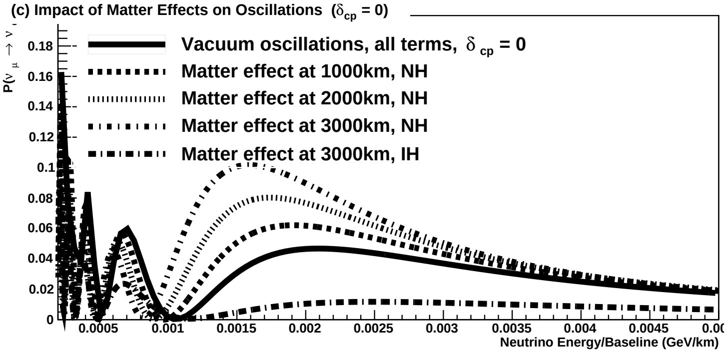
August 14, 2018

Outline

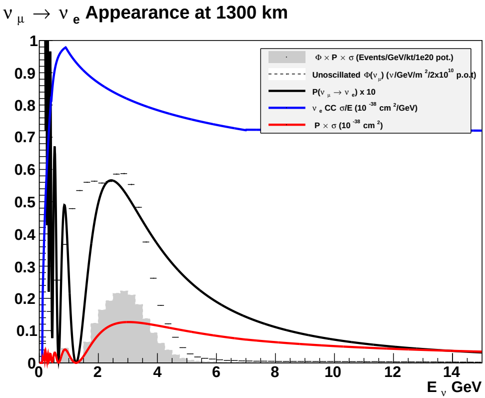
Science Requirements for the LBNF Beamline



Science Requirements for the LBNF Beamline



Science Requirements for the LBNF Beamline



Global Science Requirements of the Beam

From DUNE/LBNF's formal requirement document:

Glo-Sci-13: The neutrino beam spectrum shall cover the energy region of the first two oscillation maxima affected by muon-neutrino conversion from the atmospheric parameters.

Glo-Sci-60: The neutrino beam spectrum shall extend beyond the first maximum to higher energies, while maintaining a high signal to background ratio to obtain the maximum number of charged current signal events.

Glo-Sci-14: The neutrino beam spectrum shall be tunable so that beam with both lower peak energy (below the first oscillation node) and higher peak energy (significantly higher than the first oscillation node) can be achieved without substantial downtime that reduces the overall exposure.

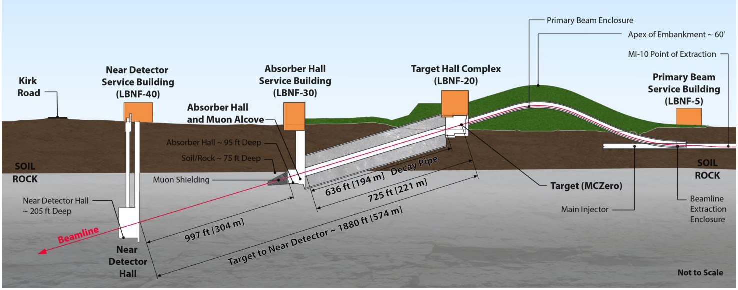
Global Science Requirements of the Beam

From DUNE/LBNF's formal requirement document:

Glo-sci-16:The beam shall be sign-selected to provide separate neutrino and anti-neutrino beams with high purity to enable measurement of CP violation mass hierarchy, and precision oscillation measurement.
Glo-sci-17:The beam shall be aimed at the far detector with an angular accuracy that allows the determination of the far detector spectrum using the near detector measurements. The angular accuracy shall not be the dominant factor in the determination of oscillation parameters.
Glo-sci-22: The beam monitoring systems shall have sufficient energy and spatial and temporal resolution that when combined with the detailed knowledge of the beam line geometry, a timely (few hours) feedback of beam performance, stability, as well as a data-driven estimate of the neutrino flux will be obtained.

LBNF Beamline Design and Optimization

Overview of the LBNF Beamline



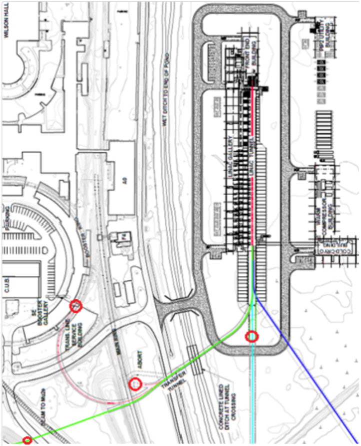
- **Primary proton beam 60-120 GeV**
- **Initial 1.2 MW beam power, upgradable to 2.4 MW**
- **Embankement allows target complex to be at grade**
- **Wide-band beam (on-axis) optimized for CP violation sensitivity**
- **Decay pipe: 194m x 4m diameter, He filled**

ND default: 574 m from target, FD: 1300 km

Proton Improvement Plan II at Fermilab

PIP-II Components

- 800 MeV linac
  - Warm Front End
  - SRF section
- Linac-to-Booster transfer line
  - 3-way beam split to: (1) Beam dump, (2) Booster & (3) Mu2e-II
- Upgraded Booster
  - 20 Hz, 800 MeV injection
    - New injection area
    - Resonant Magnet Upgrade
- Upgraded Recycler & MI
  - RF in both rings
- Conventional Facilities
  - Includes 2 empty slots at the linac end (L≈23 m)
  - Up to 1 GeV
- Cryogenic Plant

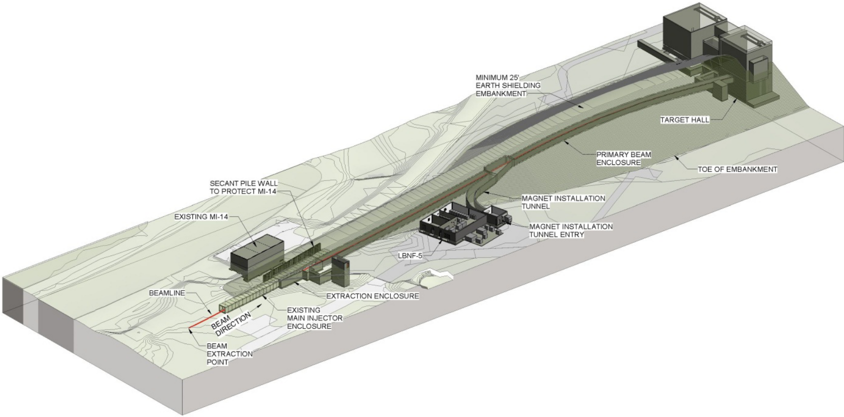


6 12/12/2017 Paul Derwent | PIP-II Conceptual Design

Recieved DOE CD1* approval Aug '18. Operations start ∼ 2027

*** DOE Critical Decision 1: Approve alternative selection and cost range. Conceptual design released**

Primary Beamline Layout

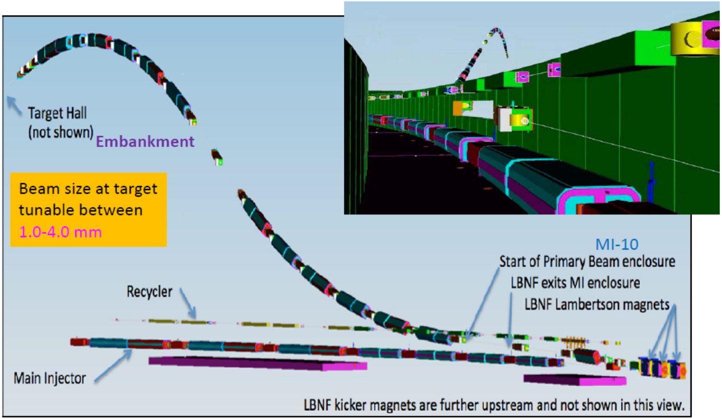


Primary Beamline Design

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

Primary Beamline Design

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

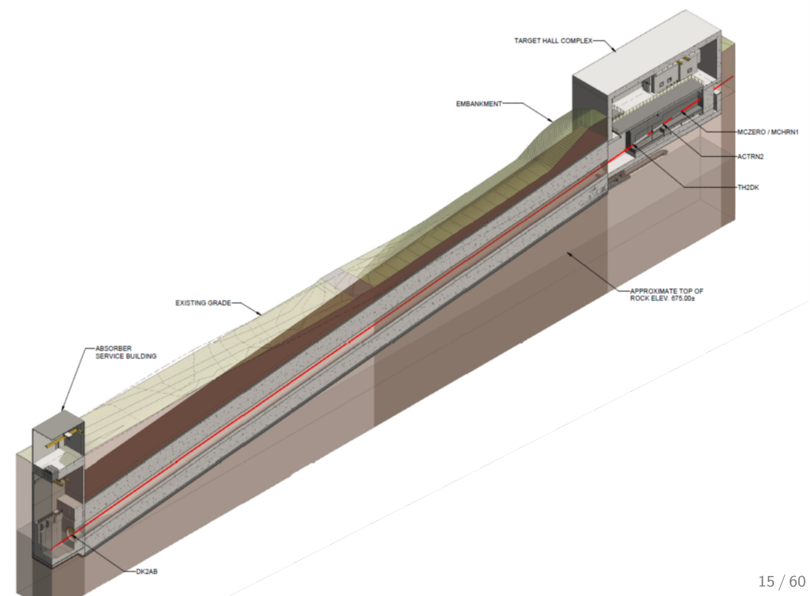


Primary Beamline Design

Table 6-3: Summary of primary-beam magnet specifications

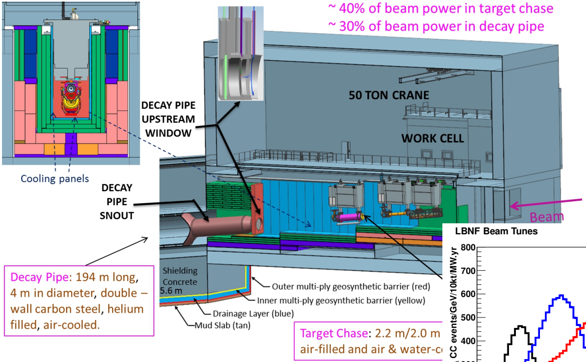
Magnet	Description	Steel Length	Nom. Strength at 120 GeV	Count
RKB type Kicker	LBNF extraction	~1.3 m	0.058 T	6
ILA	MI Lambertson	2.800 m	0.532 / 1.000 T	3
ICA	MI C Magnet	3.353 m	1.003 T	1
IDA	MI Dipole 6 m	6.100 m	1.003 - 1.604 T	13
IDD	MI Dipole 4 m	4.067 m	1.003 - 1.604 T	12
3Q120	120 inch quadrupole	3.048 m	9.189 - 16.546 T/m	17
3Q60	60 inch quadrupole	1.524 m	11.135 - 17.082 T/m	4
IDS	LBNF trim dipoles	0.305 m	Up to 0.365 T	23

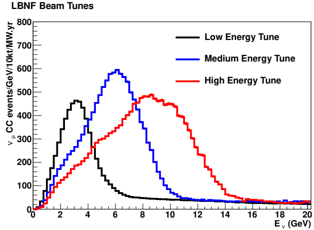
The Neurino Beamline

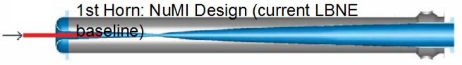


The LBNF Reference Design (up to 2015)

Initial conceptual design was of a *tunable wide-band* NuMI-style focusing:







LBNF has switched to CPV optimized focusing design with 3 horns

Optimization of flux for Physics: CP Violation

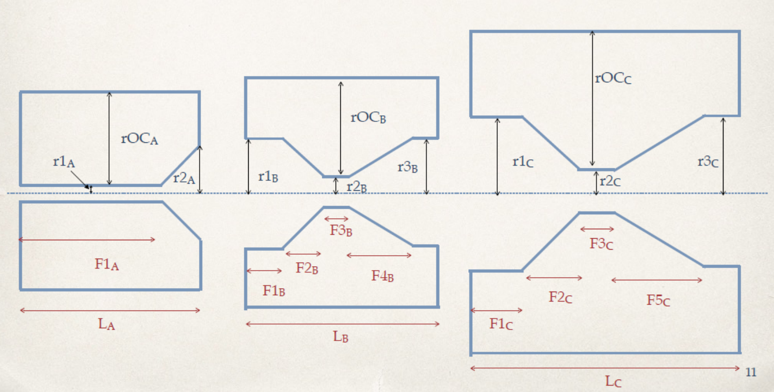
Laura Fields

- **The 2015 CD1R reference design for LBNF/DUNE is a NuMI-like movable target (segmented rectangular graphite fins with water cooling $\approx$ 1m long) and 2 modified NuMI horns 6.6m apart**
- **In Sep 2017 LBNF adopted a focusing design with 3 horns optimized using a** *genetic algorithim* **with the physics parameter to be measured (CPV sensitivity) used to gauge fitness.**
- **Target geometry is optimized at the same time, as well as proton beam energy with realistic Main Injector power profile (1.03 MW at 60 GeV to 1.2 MW at 120 GeV).**
- **Limits on horn current, diameter and length are imposed based on experience with T2K and NuMI horn manufacturing**
- **Limits on horn separation imposed based on size of target chase.**

Optimization of flux for Physics: CP Violation

Laura Fields

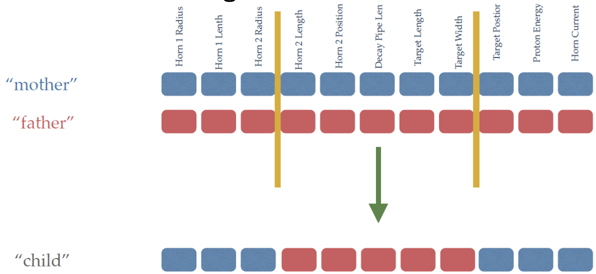
Horn parameters used in GEANT4 simulation for GA optimization:



Optimization of flux for Physics: CP Violation

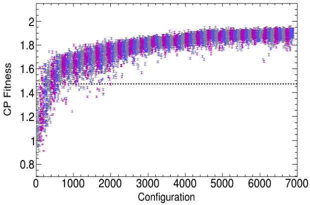
Laura Fields

Schematic of the Genetic Algorithim:



CP Fitness = minimum significance with which 75% of δ_{cp} can be determined $\neq 0$ or π for a given exposure

Fast CP Fitness estimator was determined by calculating the change in CP sensitivity given some fixed change in a single energy bin.



CP Fitness vs configuration

Optimization of flux for Physics: CP Violation

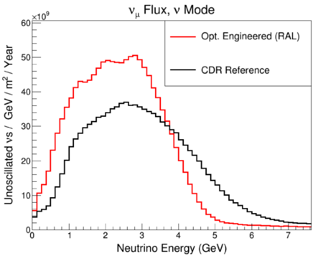
Optimized horn design with 297kA current :

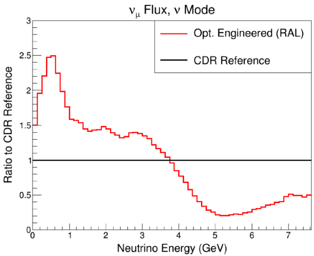
Parameter	Value		Parameter	Value
Horn A Length (mm)	2218		Horn A F1 (% of length)	53
Horn A R1 (mm)	43		Horn A OC Radius (mm)	369
Horn A R2 (mm)	33			
Horn B Length (mm)	3932		Horn C Length (mm)	2184
Horn B R1 (mm)	159		Horn C R1 (mm)	284
Horn B R2 (mm)	81		Horn C R2 (mm)	131
Horn B R3 (mm)	225		Horn C R3 (mm)	362
Horn B F1 (% of length)	31		Horn C F1 (% of length)	20
Horn B F2 (% of length)	22		Horn C F2 (% of length)	9
Horn B F3 (% of length)	2		Horn C F3 (% of length)	7
Horn B F4 (% of length)	16		Horn C F4 (% of length)	35
Horn B OC Radius (mm)	634		Horn C OC Radius (mm)	634
Horn B Position (mm)	2956		Horn C Position (mm)	17806

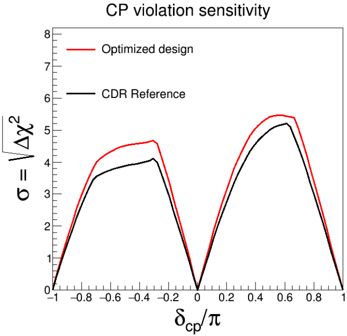
Optimized target is 4λ (2m C) with $\sigma_{\mathrm{beam}} = 2.7$mm, $E_p \sim 110$ GeV

Optimization of flux for Physics: CP Violation

Laura Fields



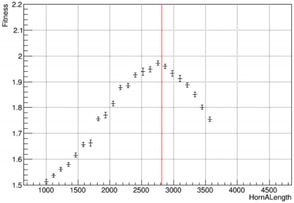




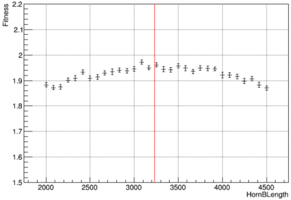
Computationally advanced optimization techniques = significant gain in flux and CPV sensitivity from *many* small changes

Gain in sensitivity ≡ 70% increase in FD mass

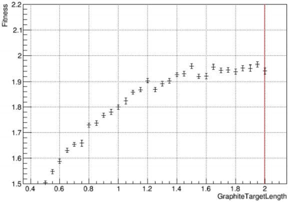
Scan over some sample optimization parameters:



Horn A length

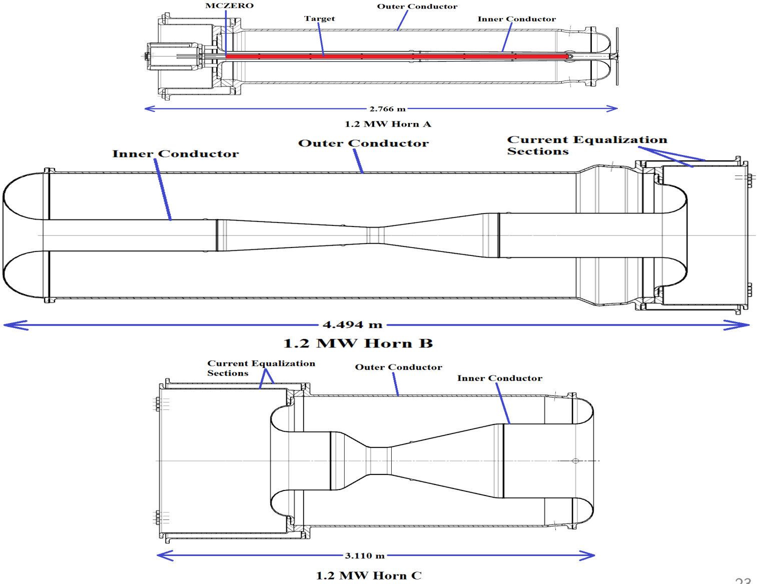


Horn B length



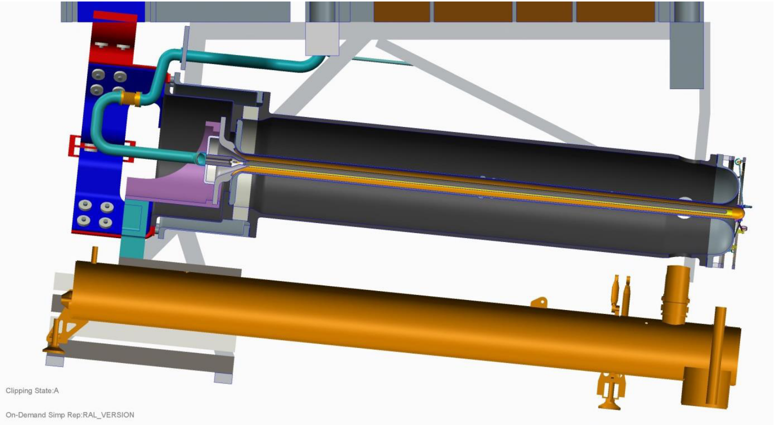
Target length

Engineering the neutrino beam optimized design



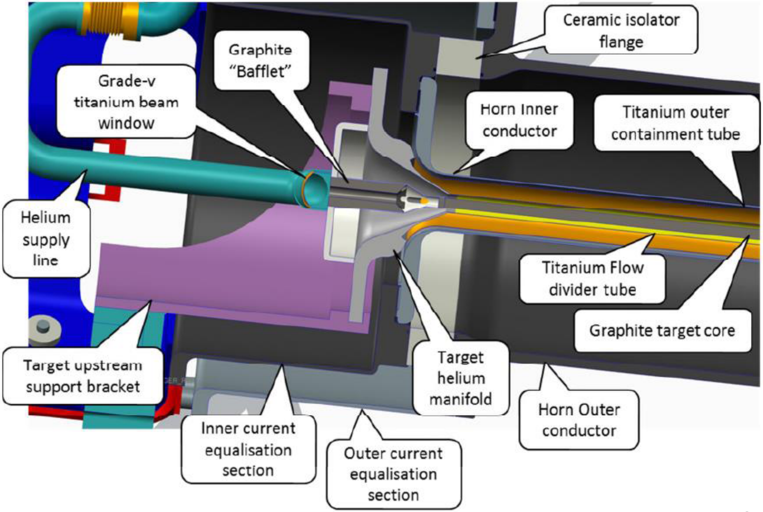
Engineering the neutrino beam optimized design

Horn A and 2m target design



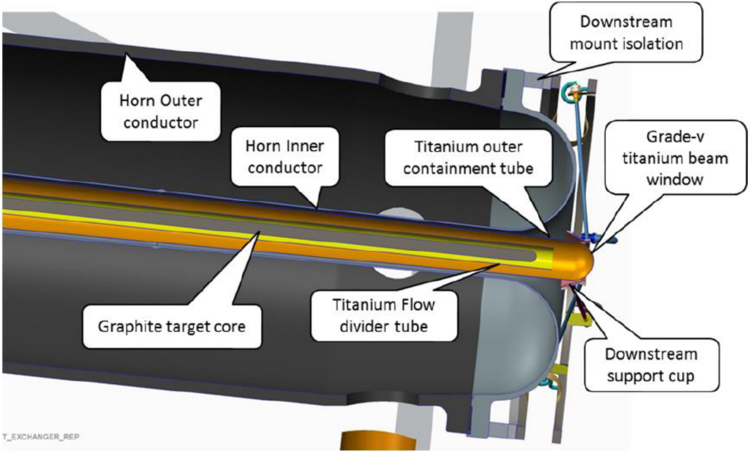
Engineering the neutrino beam optimized design

Upstream section of target in Horn A (RAL design)

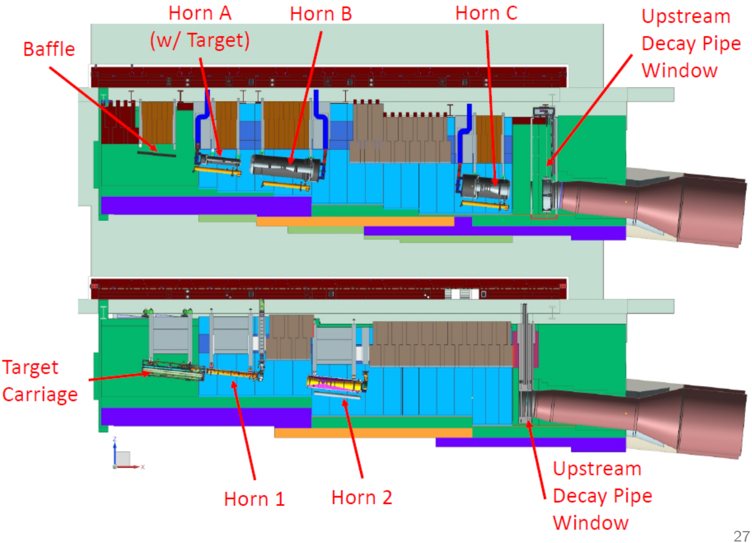


Engineering the neutrino beam optimized design

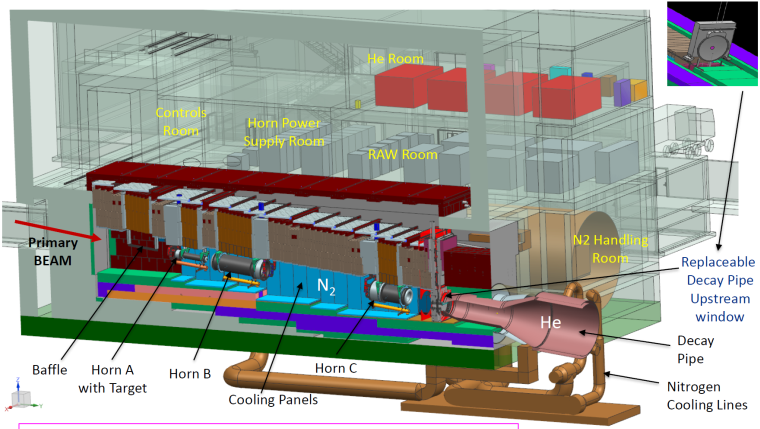
Downstream section of target in Horn A (RAL design)



Target hall layout 3-horn optimized vs CD1R reference designs:

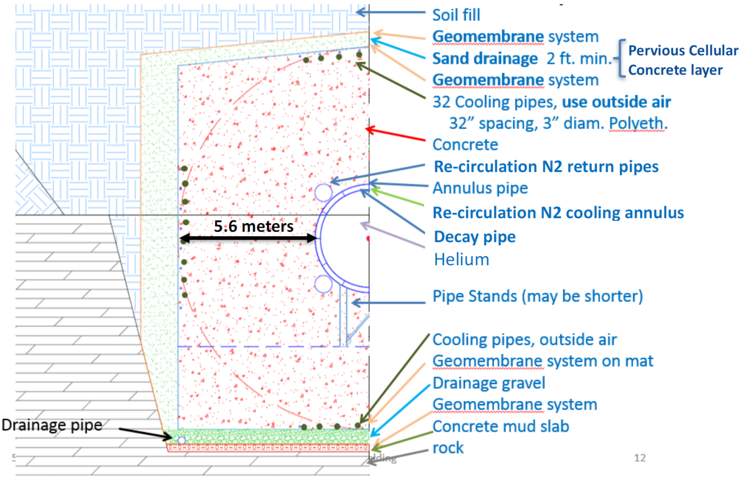


Target Hall for Optimized Design



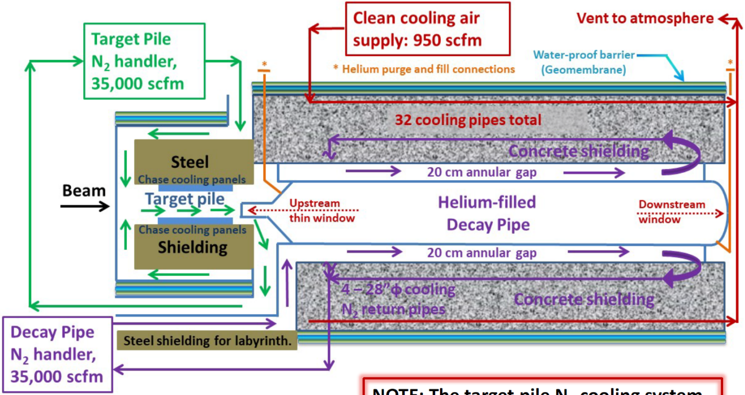
Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (replaceable cooling panels).

Decay Pipe Design



Decay pipe is 194m long and 4m in diameter, He filled

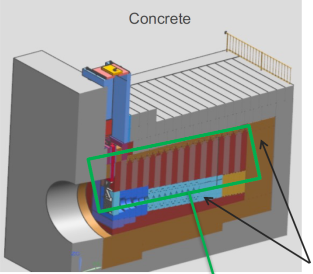
Decay Pipe Cooling



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

Hadron Absorber Conceptual Design 2015-2017

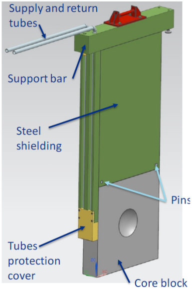
Absorber Core (water cooled)



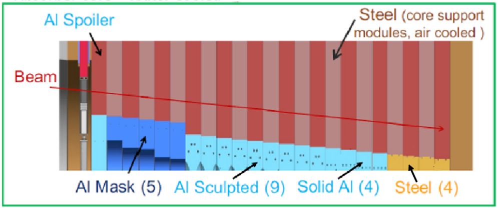
- Made of removable, water-cooled Al and Steel "T-Blocks" (based on NuMI T-Block design)
- Gun drilled water channels in core blocks.
- Flexible, modular design that can be repaired/replaced or upgraded in the future.

Steel
(air cooled)

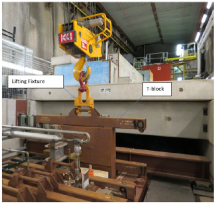
Absorber Core Module Assy.



Absorber Core – Water Cooled

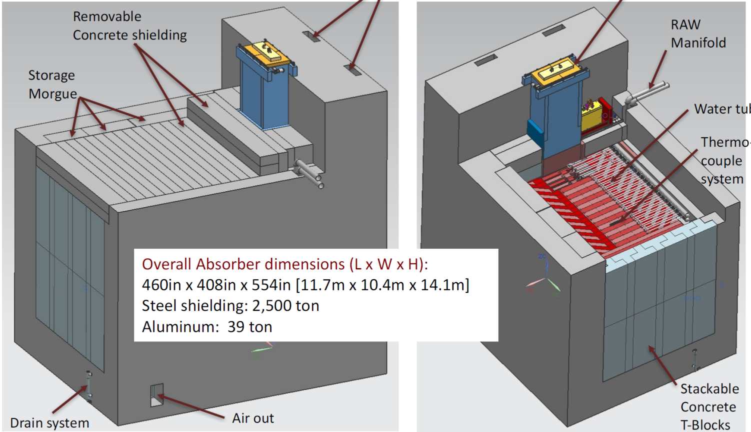


NuMI T-Block



Hadron Absorber Conceptual Design 2015-2017

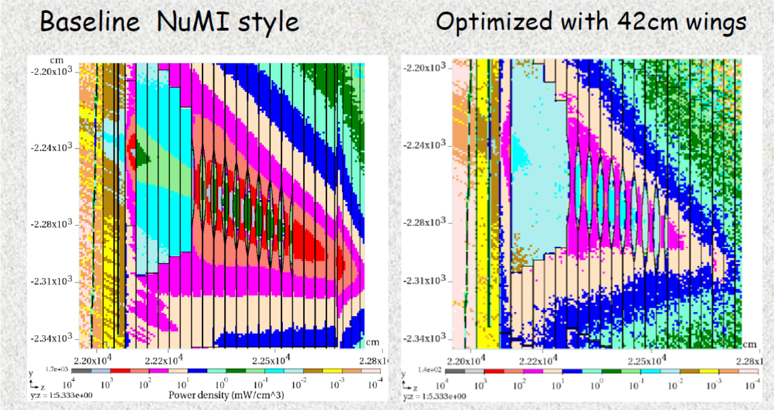
Absorber Design



Overall Absorber dimensions (L x W x H):
460in x 408in x 554in [11.7m x 10.4m x 14.1m]
Steel shielding: 2,500 ton
Aluminum: 39 ton

LBNF Absorber Energy Deposition

MARS15 simulation (N. Mokhov):



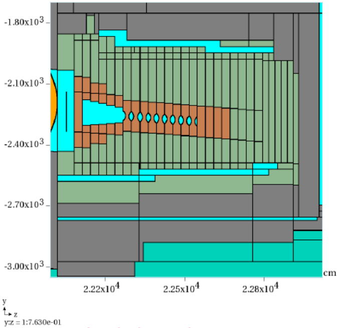
Optimized focusing design and wings added to target could reduce peak energy deposition in absorber core 8-12 ×.

Optimizing Absorber Design

Absorber design at CD1R (2015) was not optimized - non-uniformity makes monitoring of tertiary beam muons difficult. Uniform absorber design developed in 2017-2018:

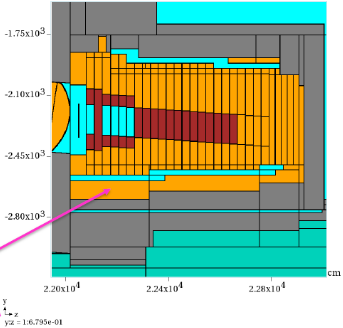
Ref. Hadron Absorber (RHA)

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

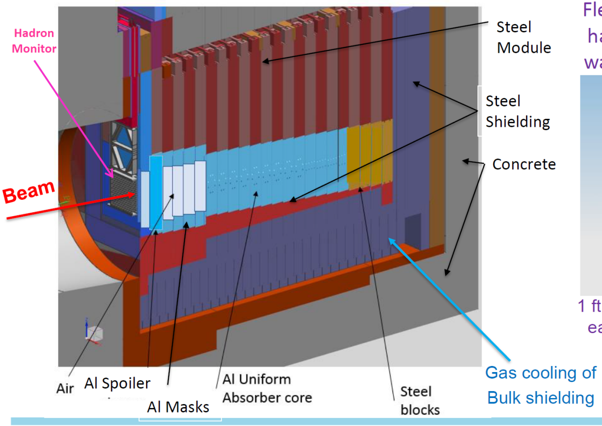


CFD simulation points to temperature reduction by 40% (89^{0}C) in the optimized design with UHA

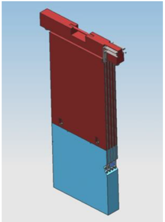
Uniform absorber is now LBNF baseline design

Optimizing Absorber Design

Large diameter core with uniform density to enable good muon monitoring



Flexible, modular hanger design of water cooled core



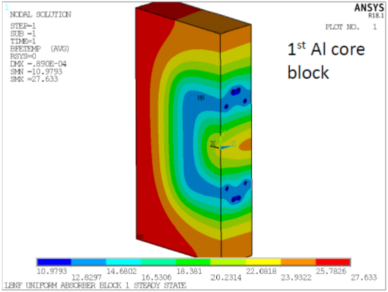
1 ft thick core blocks are easily replaceable via Remote Handling

22 Jim Hylen | High-power Neutrino Target Stations 8/14/2018 Fermilab

Optimizing Absorber Design

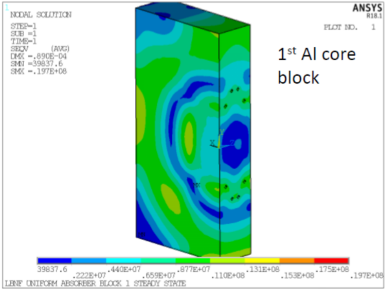
MARS15-ANSYS analysis of the uniform absorber core in the optimized beam completed for normal case. Spoiler and steel blocks are cool and show low stress:

UHA – 28 C Max (RHA 88 C Max)



Temperature

UHA – 20 MPa Max (RHA 103 MPa Max)



Pressure

Accident case has been analyzed and is fine

Beam Flux Systematics with Optimized Design

Neutrino Beam Flux Comparisons

(For 50 kton.years* of exposure. No detector effects)

Experiment	Baseline	$\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$ δ_{CP} range
Current Experiments				
T2K 30 GeV, 750 kW 9×10^{20} POT/year	295km (off-axis)	900	< 1	40 - 70
MINOS LE 120 GeV, 700 kW 6×10^{20} POT/year	735km	11,000	115	230-340
NOνA 120 GeV, 700 kW 6×10^{20} POT/year	810km (off-axis)	1500	10	120 - 200
Future Experiments				
LBNF/DUNE LE† 80 GeV, 1.1MW 1.5×10^{21} POT/year	1,300km	4300	160	350 - 600
LBNF/DUNE ME† 120 GeV, 1.2MW 1.1×10^{21} POT/year	1,300km	12,000	690	290 - 430
T2HK 30 GeV, 1.3 MW		(see T2K numbers)		

* Facility duty factor taken into consideration

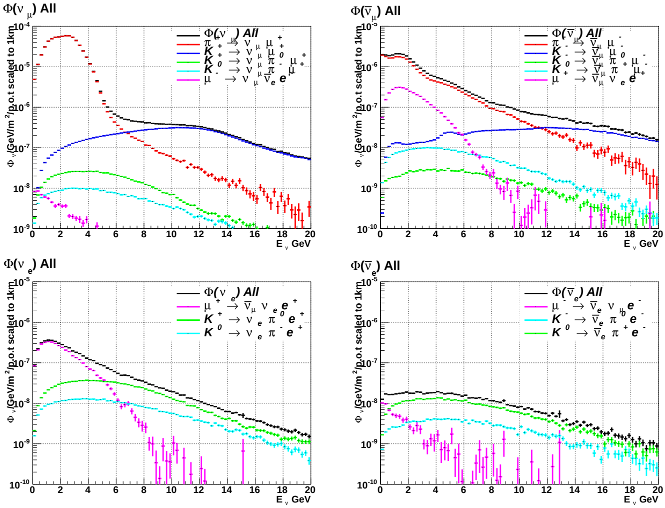
† 2012 LBNE CDR Reference Design with NuMI style focusing

Future LB experiments expect $\mathcal{O}(1000)$ $\nu_\mu \to \nu_e$ CC events

Need to control *total* systematics to a few %

Flux components at near and far

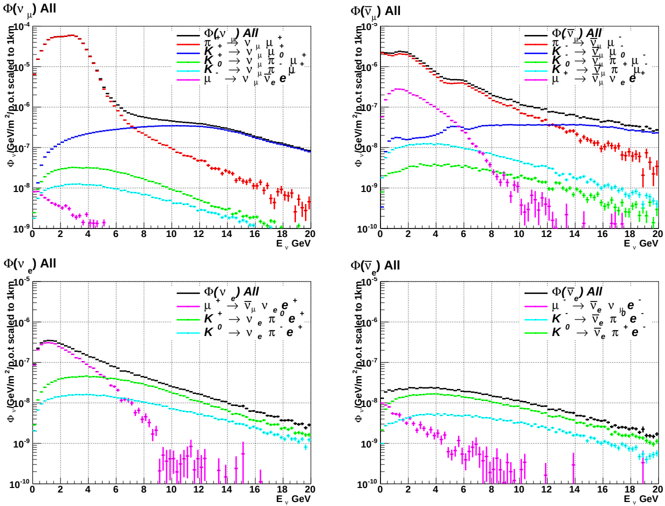
ND 570



Baseline scaled to 1km from middle of decay channel

Flux components at near and far

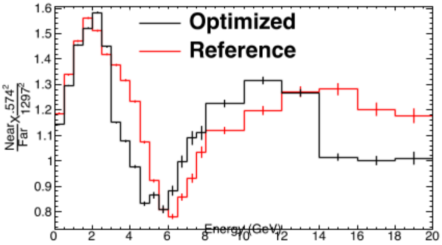
FD 1300km



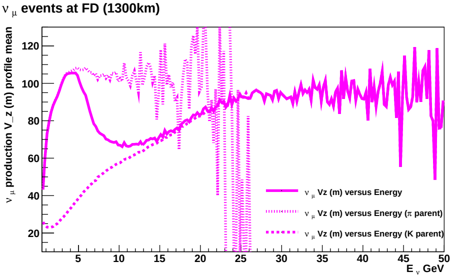
Baseline scaled to 1km from middle of decay channel

Near to Far Extrapolation

Simple ratio of Near/Far spectrum:



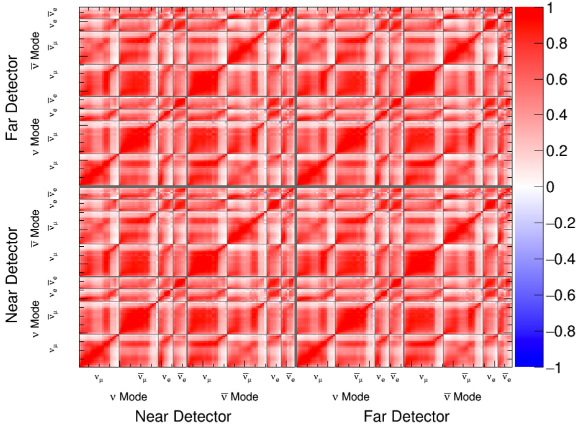
Neutrino parent decay location in decay pipe:



π/K decay kinematics and decay channel geometry are primary reason for strange shape of N/F ratio

Near to Far Extrapolation

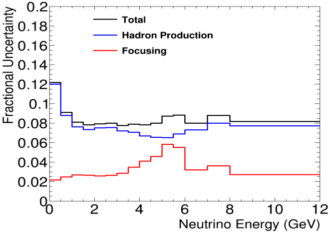
To correctly relate near to far fluxes - need to use a correlation matrix:



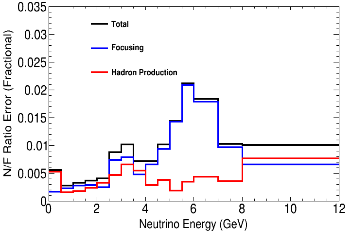
Flux correlation matrix comes from simulation and is highly correlated

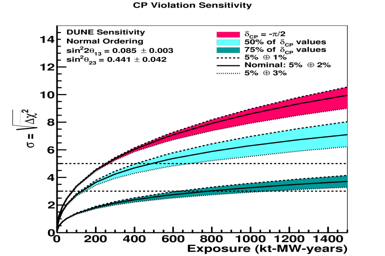
Flux Uncertainties

Uncertainty on ND flux prediction



Residual uncertainty at FD





How well do we actually trust the simulation to correctly estimate the uncertainties on near → far extrapolation?

A Spectrometer for Hadron Flux Measurements?

Proposal by Laura Fields at Fermilab:

The **LBNF Spectrometer** is a concept for a thick-target hadron production **measurement after the focusing horns**. It would involve a **replica of the LBNF** target and horns in an external beamline at Fermilab. In addition to hadron production in the target, the spectrometer would also **measure hadron production and absorption in the horns and the effects of the magnetic fields** in the horns.

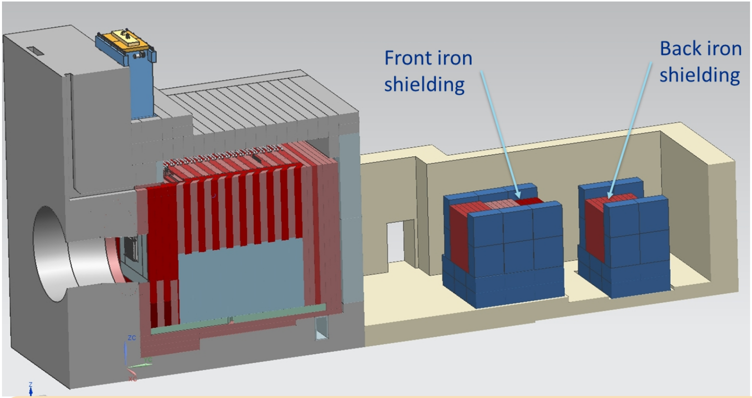
Detector technology is always challenging

Need to get more people interested and involved to succeed

Monitoring the Neutrino Flux Stability

Muon Beam Monitors

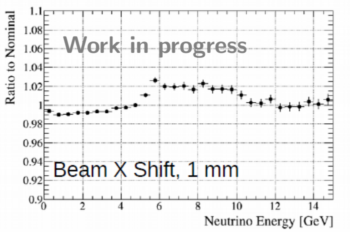
Layout of Muon Alcove and Shielding

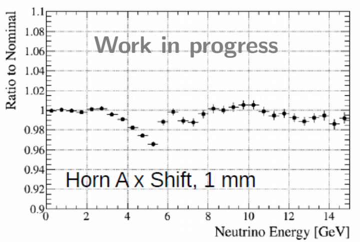


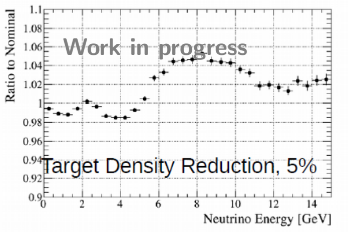
High intensity makes it difficult to measure μ spectrum accurately. With a 2.4 MW beam, the absorber thickness is too large to sample the lower energy muons. But these systems play an essential role in monitoring *flux stability*

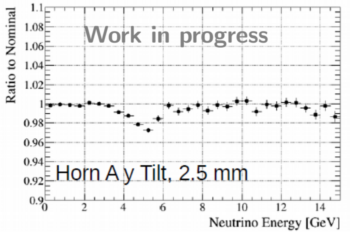
Correlation between neutrino and muon spectrum

ν Spectrum Changes



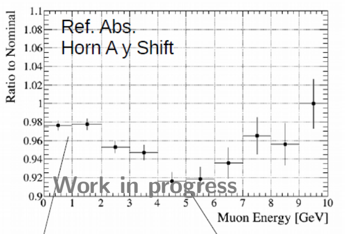


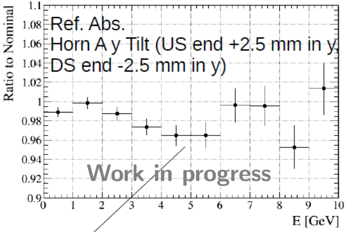




Correlation between neutrino and muon spectrum

μ Spectrum Changes





Reduction in total flux

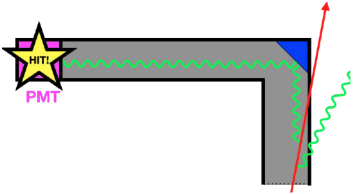
Shape changes at max near 5 GeV

Changes are v. small - need novel detector concepts

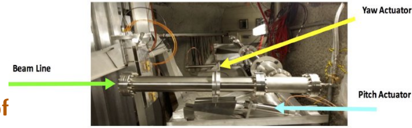
Muon Monitor Technologies under R&D

- **Array of ionization detectors: Measures muon beam center and intensity. Spill by spill monitoring of beam stability. Both diamond and silicon under study**
- **Threshold gas Cherenkov detector (R&D): Uses signal intensity at different gas pressure and angles to extract rough muon spectrum.**
- **Stopped muon counters (R&D): separate stations with steel shielding in between could measure muon flux at several energies. Better measurement of beam flux spectrum and composition.**

Gas Cherenkov counter concept:

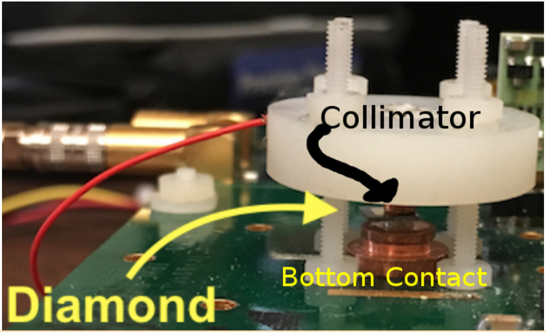


Prototype in NuMI beamline:



Currently only ionization detectors included in the beam design.

Ionization detector: Diamond Detector Prototyoe



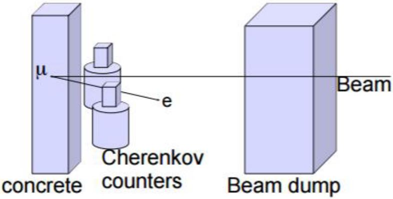
Use polycrystal chemical vapor deposition (pCVD) diamond - detects ionizing radiation when a large voltage potential (1V per m of thickness) is applied across two sides of the diamond. Diamond is radiation hard.

pCVD detector prototype installed in NuMI during 2018 shutdown.

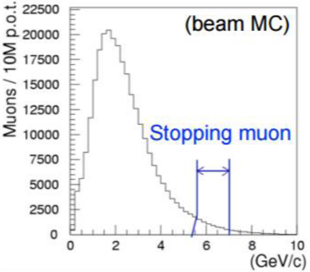
Stopped Muon Concept

From K. Hiraide, *Muon monitor using the decay electrons*, NBI2003 Workshop

Strategy



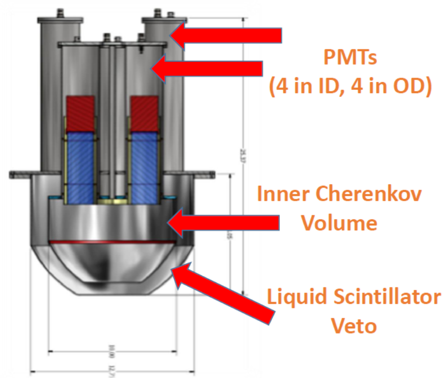
- Counting the decay electrons from muons stopping at the wall of μ-pit
- Measuring spatial and time distributions of events



- Energy loss of muons in the beam dump
- Range of electrons in the concrete

We can measure muons of
5.2~7.0GeV/c
by counting the decay electrons

Stopped Muon Prototype



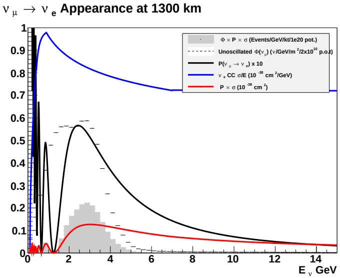
Prototypes being commissioned with cosmics.

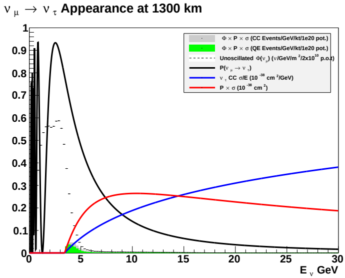
Possible Future Upgrades to the LBNF Beamline to enhance the DUNE Physics Program

Tunability of beam and ν_τ Flux (v. preliminary)

NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \to \nu_\tau$ with high statistics.

2015 two horn optimized design $E_p = 66$ GeV:

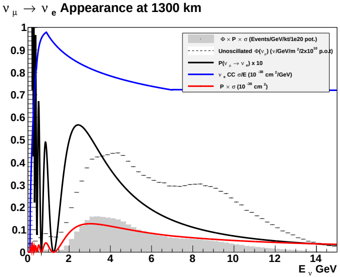


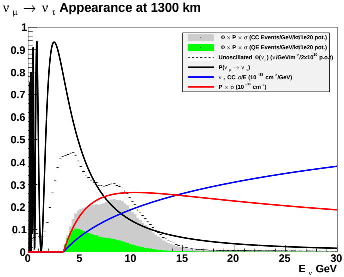


$\nu_\mu \to \nu_e$ 290 events $\nu_\mu \to \nu_\tau$ 60 events
in 40 ktons, 1 year at 1.2 MW

NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \rightarrow \nu_\tau$ with high statistics.

LBNF target -2m from horn 1, NuMI focusing 230 kA, horns 17m apart





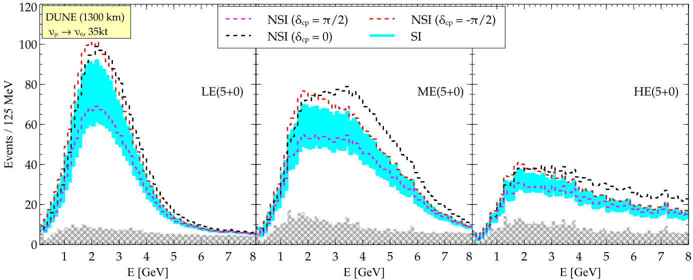
$\nu_\mu \rightarrow \nu_e$ **330 events** $\quad\quad$ $\nu_\mu \rightarrow \nu_\tau$ **700 events**

in 40 ktons, 1 year at 1.2 MW

Increase ν_τ appearance 10x!!!

Increase high energy ν_e appearance - good for NSI/Sterile searches

Study NSI sensitivity with GLoBeS using $\nu_\mu \rightarrow \nu_{\mu,e}$ and 3 sample LBNF-like beam tunes : LE, ME and HE*.
NSI parameters used:
$|\epsilon_{e\mu}| = 0.04, \ |\epsilon_{e\tau}| = 0.04, \ \epsilon_{ee} = 0.4, \ \phi_{e\mu=0}, \ \phi_{e\tau}$

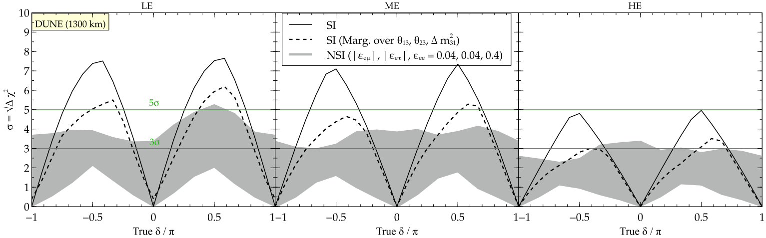


NSI effects in $\nu_\mu \rightarrow \nu_e$ are larger at higher energy

* 2 NuMI horns, 230kA, 6.6m apart and horns were not moved for higher energy beam tunes (non-optimal beams). Decay pipe was assumed to be 250m.

SI/NSI Separation with Different Beams

M. Masud, P. Mehta, M. Bishai arXiv:1704.08650



SI/NSI separation metric:

(the abbreviations *tr* and *ts* indicate *true* and *test* respectively.)
Thus for the NSI-SI separation,

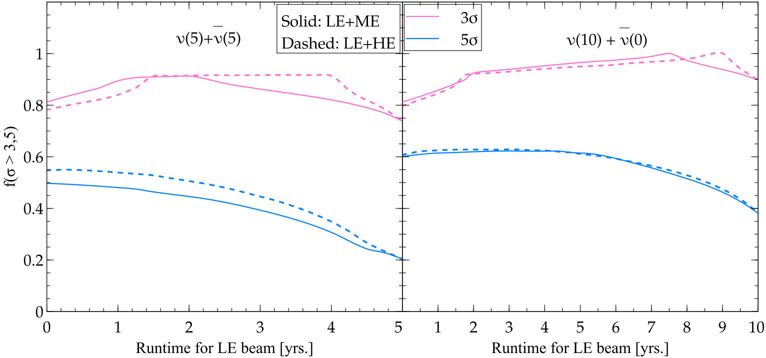
$$\chi^2(\delta_{tr}) = \min_{\delta_{ts}} \sum_{i=1}^{x} \sum_{j}^{2} \frac{\left[N^{i,j}_{NSI}(\delta_{tr}, |\varepsilon|, \varphi) - N^{i,j}_{SI}(\delta_{ts} \in [-\pi, \pi])\right]^2}{N^{i,j}_{NSI}(\delta_{tr}, |\varepsilon|, \varphi)} \quad (2)$$

where, we have marginalised over the standard CP phase δ in the test dataset. This χ^2 was calculated using a set of conservative values of the NSI parameters (see Table 2).

SI/NSI Separation with Different Beams

M. Masud, P. Mehta, M. Bishai arXiv:1704.08650

Fraction of SI δ_{cp} for which SI/NSI can be separated at the $3/5\sigma$ level:



Can achieve 3σ separation for $> 80\%$ of true δ_{cp}

No beam optimization attempted yet!

Summary and Conclusions

Summary and Conclusions

- **The LBNF beam design is advancing towards a preliminary design for CD2 (expected end of 2019)**
- **The CPV optimized neutrino beamline design with 3 horns is now the baseline design**
- **The challenging design of Horn A with a 4λ graphite target is proceeding**
- **The simplified hadron absorber redesign for the optimized beam is well advanced.**
- **A "real-time" beam monitoring system is a requirement for the LBNF beamline, and R&D for a muon monitoring system is proceeding but is still very challenging.**
- **New physics capabilities with high energy beams produced from the 2015 CD1R reference design are being explored.**
- **A full evaluation of the flux uncertainties from the optimized beam has been carried out. Uncertainties are at the 1% level in the oscillation region.**