Long-Baseline Neutrino Beams at Fermilab

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Existing Fermilab Neutrino Beams
Planned New Neutrino Beam
Beams of several baselines

• Long Baselines (oscillation physics)
  - NuMI to MINOS: $L/E \approx 735 \text{ km} / 3 \text{ GeV} \approx 250 \text{ km/GeV}$
  - NuMI to NOvA: $L/E \approx 810 \text{ km} / 2 \text{ GeV} \approx 400 \text{ km/GeV}$
  - LBNE $L/E \approx 1300 \text{ km} / 2.5 \text{ GeV} \approx 430 \text{ km/GeV}$

• Short Baseline (oscillation physics)
  - BNB to MiniBoone: $L/E \approx 0.6 \text{ km} / 0.6 \text{ GeV} \approx 1 \text{ km/GeV}$

• Shorter Baseline (experiments assume no oscillation effects)
  - NuMI to MINERvA: $L/E \approx 1 \text{ km} / 3 \text{ GeV} \approx 0.3 \text{ km/GeV}$
  - BNB to SciBooNE: $L/E \approx 0.1 \text{ km} / 0.6 \text{ GeV} \approx 0.15 \text{ km/GeV}$
Beams of several baselines

- **Long Baselines (oscillation physics)**
  - NuMI to MINOS: \( L/E \approx 735 \text{ km} / 3 \text{ GeV} \approx 250 \text{ km/GeV} \)
  - NuMI to NOvA: \( L/E \approx 810 \text{ km} / 2 \text{ GeV} \approx 400 \text{ km/GeV} \)
  - LBNE: \( L/E \approx 1300 \text{ km} / 2.5 \text{ GeV} \approx 430 \text{ km/GeV} \)

- **Short Baseline (oscillation physics)**
  - BNB to MiniBoone: \( L/E \approx 0.6 \text{ km} / 0.6 \text{ GeV} \approx 1 \text{ km/GeV} \)

- **Shorter Baseline (experiments assume no oscillation effects)**
  - NuMI to MINERvA: \( L/E \approx 1 \text{ km} / 3 \text{ GeV} \approx 0.3 \text{ km/GeV} \)
  - BNB to SciBooNE: \( L/E \approx 0.1 \text{ km} / 0.6 \text{ GeV} \approx 0.15 \text{ km/GeV} \)
NuMI Beam

See also talks by Jeff Hartnell, Phil Adamson, Mathew Meuther

Beam Layout

- Optimized for high energy and tuneability (designed before oscillation parameters were known)
NuMI Beam – Tuneability of on-axis spectrum

- Beam energy can be changed by moving the target in (low energy) and out (high energy) of first horn.

- MINOS running has mainly been in the LE tune.
Neutrino Mode

Monte Carlo

Neutrino mode
Horns focus $\pi^+, K^+$

$\nu_\mu = 91.7\%$
$\bar{\nu}_\mu = 7.0\%$
$\nu_e + \bar{\nu}_e = 1.3\%$

Target

Focusing Horns

120 GeV protons from MI

Decay Pipe

2 m

Alex Himmel
Antineutrino Mode

**Monte Carlo**

Neutrino mode  
Horns focus $\pi^+, K^+$  
$\nu_\mu = 91.7\%$  
$\overline{\nu}_\mu = 7.0\%$  
$\nu_e + \overline{\nu}_e = 1.3\%$

Antineutrino mode  
Horns focus $\pi^-, K^-$  
$\overline{\nu}_\mu = 39.9\%$  
$\nu_\mu = 58.1\%$  
$\nu_e + \overline{\nu}_e = 2.0\%$

120 GeV protons from MI  

Target  
Focusing Horns  

Decay Pipe  
2 m  
15 m  
30 m  
675 m  

Alex Himmel
NuMI Off-Axis Beam for NOvA

- NOvA will operate with ME tune, 14 mrad off-axis => 2 GeV narrow band beam.
NuMI Off-Axis Beam for NOvA

- NOvA beam has excellent purity in terms of $\nu_e$ background in oscillation region.
NuMI Off-Axis Beam for NOvA

- NOvA beam has excellent purity in terms of $\nu_e$ background in oscillation region.
NuMI Beam Power – Maximum achieved for 1 hour

- Beam power shows increasing trend over last few months
- Exceeded 400 kW in MI for 1 hour in “normal” running
- Will push again when target is installed
<P> = 250 kW incl. downtime
NuMI Beam Power – Weekly Average

\[ \langle P \rangle = 250 \text{ kW incl. downtime} \]
NuMI Beam Power – Weekly Average

\[ \langle P \rangle = 250 \text{ kW incl. downtime} \]

2.4 MW x 10^7 sec

H.Budd

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# NuMI Target History

| Target Design specification | Max. Proton/pulse | Max. Beam Power | Integrated Protons on Target |
|-----------------------------|------------------|-----------------|-----------------------------|
| Target Design specification | 4.0e13 p.p.p. at 120 GeV | 400 kW | 3.7 e20 p.o.t. or 1yr minimum lifetime |
| 1st target                  | 3.0 e13 p.p.p.   | 270 kW          | 1.6 e20 p.o.t.             |
| 2nd target                  | 4.0 e13 p.p.p.   | 340 kW          | 6.1 e20 p.o.t.             |
| 3rd target                  | 4.4 e13 p.p.p.   | 375 kW          | 3.1 e20 p.o.t.             |
| 4th target                  | 4.3 e13 p.p.p.   | 375 kW          | 0.2 e20 p.o.t.             |
| 5th target                  | 4.0 e13 p.p.p.   | 337 kW          | 1.3 e20 p.o.t.             |
| 6th target                  | 3.5 e13 p.p.p.   | 305 kW          | 0.2 e20 p.o.t.             |
NuMI Target History

![Integrated POT Graph](image)

- NT-01: 1E+20
- NT-02: 6E+20
- NT-03: 3E+20
- NT-04: 1E+00
- NT-05: 1E+00
- NT-06: 1E+00

specification
## Target Summary

| Target | Fate |
|--------|------|
| NT-01  | Zombie target – now running |
| NT-02  | ~15% Radiation damage to graphite |
| NT-03  | Failure in ceramic at upstream end of can |
| NT-04  | Unknown water leak, Be windows destroyed |
| NT-05  | Water leak at DS turnarounds |
| NT-06  | Water leak upstream |
NuMI Beam Power Upgrades for NOvA

- Injection and Slip Stacking in Recycler Ring
  - Cut $2/3$ second for injection from cycle
  - 12 batches from Booster instead of 11
- Single turn transfer to MI
- Ramp to 120 GeV
  - Faster ramp: 1.333 second
  - All 12 to NOvA target: $\sim 4.9 \times 10^{13}$ 706 kW
- 1.333 second cycle
  - 9 Hz demand on Booster
  - 12 consecutive pulses
  - 1.4$ \times 10^{17}$/hour
- Target Station:
  - New target design
  - New Horn configuration
LBNE Beam

See also talk by Vaia Papadimitriou

• We need a new beamline for LBNE:
  - Need longer baseline (see my WG1 talk earlier today)
    Longest baseline along NuMI direction ~ 1000 km
    (where beam axis is ~15 km above ground)
  - Need to plan for higher-power Project X beam
    Power limitation of NuMI line is certainly << 2 MW
  - Need beam optimized for lower energy and smaller \( \nu_e \) component => shorter, wider decay pipe.
  - Need beam pointed to Homestake / Sanford Lab
LBNE Beam – High-Level Requirements

• Beam pointed to Homestake => 1300 km baseline
• Broad-band beam, covering 1\textsuperscript{st} and 2\textsuperscript{nd} maxima (2.5 and 0.8 GeV)
• Minimize high energy tail above \~5 GeV
• Minimize $\nu_e$ and “wrong-sign” $\nu_\mu$
• Tunable => proton beam 60 < E < 120 GeV
• Design for initial power = 700 kW, upgradeable to >2 MW
• Beam and Near Detector on Fermilab site
• Stringent radiation safety requirements
• Minimize cost!
LBNE Beamline Major Alternatives

Extraction from MI-60
LBNE Beamline Major Alternatives

Extraction from MI-60 or MI-10
LBNE Beamline Major Alternatives

Extraction from MI-60 or MI-10

Beamline above or below grade
The LBNE design selected for physics studies maximizes the $\nu_e$ appearance signal at 1300 km.

**Target:** Carbon target, $r=0.6\text{ cm}$, $l=80\text{ cm}$, $\rho = 2.1 \text{ g/cm}^3$. Located 30 cm from Horn1.

**Horns:** 2 Al NuMI Horns, 6 m apart, 250 kA.

**Decay Pipe:** $r=2\text{ m}$, $l=280\text{ m}$, He filled/evacuated.

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**Aug 2010 Neutrino Beam**

- $\nu_\mu$, $\nu_e$, Anti-$\nu_\mu$, Anti-$\nu_e$

**Aug 2010 Anti-Neutrino Beam**

- $\nu_\mu$, $\nu_e$, Anti-$\nu_\mu$, Anti-$\nu_e$
The LBNE design selected for physics studies maximizes the $\nu_e$ appearance signal at 1300km.

**Target:** Carbon target, $r=0.6\text{cm}$, $l=80\text{cm}$, $\rho = 2.1 \text{ g/cm}^3$. Located -30cm from Horn1.

**Horns:** 2 Al NuMI Horns, 6m apart, 250 kA.

**Decay Pipe:** $r=2\text{m}$, $l=280\text{m}$, He filled/evacuated.

Maybe a little more optimistic that what we will be able to afford.

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LBNE Beamline Design Issues

- Radiation safety with above grade beam
  - Prompt radiation at site boundary
  - Tritium isolation with decay pipe and absorber partially in the aquifer.

- Decay pipe length and diameter (cost vs. performance, space relative to site boundary)

- Target lifetime – assume that this will be solved by NOvA for 700 kW beam, but work is required towards 2 MW

- Difficult to obtain substantial flux at 800 MeV = 2\textsuperscript{nd} oscillation max
  - Lower beam energy helps
  - Innovative target designs?
Robust geomembrane system required to isolate aquifer from Tritium in decay pipe shielding. (Landfill technology)
LBNE Beam – Vary decay pipe dimensions

Decay pipe length

Decay pipe diameter

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B. Lundberg
LBNE Beam – Flux at 2\textsuperscript{nd} Oscillation Maximum

\[ \nu_\mu \rightarrow \nu_e ; \sin^2 2\theta_{13} = 0.05 \]

- Reminder about rates - per 100kt per year at 700kW (over bkg):

\[ E < 1.2 \text{ GeV} \rightarrow 11 \text{ events} \]

\[ 1.2 < E < 6 \rightarrow 360 \text{ events} \]
Flux at 2\textsuperscript{nd} Max – Effect of Proton Energy
Flux at 2nd Max – Effect of Proton Energy

Unoscillated $\nu_\mu$ Flux at 1300 km

- $E_{p^+} = 120$ GeV
- $E_{p^+} = 90$ GeV
- $E_{p^+} = 60$ GeV
- $E_{p^+} = 50$ GeV
- $E_{p^+} = 40$ GeV
- $E_{p^+} = 30$ GeV

Lower Beam Power

Fermilab
Flux at 2nd Max – Innovative Targets?

Hybrid target design: NEW

Increases $\pi$ flux at 2nd maximum by $\sim 50\%$

Decreases $\pi$ flux $> 20$ GeV ($E_\nu > 8$ GeV) by $50\%$

M.Bishai
Flux at 2nd Max – Innovative Targets?

Increases $\pi$ flux at 2nd maximum by $\sim 50\%$

Decreases $\pi$ flux $>20$ GeV ($E_\nu > 8$ GeV) by 50%
Summary

- NuMI Beam is operating at a typical weekly average power of 250 kW, including downtime. Peak hourly average power = 400 kW.
- NOvA upgrades will increase beam power to 700 kW.
- LBNE beam is under design.
  - Higher power capability to > 2 MW
  - Optimizing spectrum for 1300 km baseline
  - Studying shallow options and different decay pipe dimensions for cost reduction.

More details in Vaia Papadimitriou’s talk in WG3 earlier today.

Many thanks to those who helped me prepare this talk and from whom I took slides.