Design of the LBNF Beamline

Jim Hylen, for the DUNE collaboration
Fermilab Accelerator Division

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LBNF = Long Baseline Neutrino Facility

Takes protons from Fermilab accelerator

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

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

PIP-II has DOE CD0 approval

Synchrotron or linac

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 1\textsuperscript{st} and 2\textsuperscript{nd} oscillation peaks ($E_\nu \sim 2.4$ and 0.8 GeV for $L=1300$ km)

• Does 3-$\nu$ 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
  ➢ $\nu$ vs $\bar{\nu}$ selection done by beam focusing $\pi^+$ or $\pi^-$ (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 $E_\nu$ 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

Optimized system:
• Increases flux in oscillation region
• Decreases flux in high-energy tail
• Increases CP sensitivity

Sensitivity for (detector) x (beam) of 300 kT MW years exposure
• includes derating for beam down-time
• DUNE reference = 40 kT detector

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

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

See Rowan Zaki’s presentation
“Optimization of the LBNF Neutrino Beam”
Have completed conceptual design of optimized horns

**Temperature and Stress looks OK**

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

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.

<table>
<thead>
<tr>
<th>System</th>
<th>RD (kW)</th>
<th>OD (kW)</th>
<th>OD/RD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Pile</td>
<td>952</td>
<td>1238</td>
<td>1.30</td>
</tr>
<tr>
<td>Decay Pipe Region</td>
<td>452</td>
<td>542</td>
<td>1.20</td>
</tr>
<tr>
<td>Hadron Absorber</td>
<td>786</td>
<td>400</td>
<td>0.51</td>
</tr>
<tr>
<td>Misc: infrastructure, binding energy, sub-threshld</td>
<td>144</td>
<td>151</td>
<td>1.05</td>
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<tr>
<td>Neutrino power</td>
<td>66</td>
<td>69</td>
<td>1.05</td>
</tr>
<tr>
<td>Total</td>
<td>2400</td>
<td>2400</td>
<td></td>
</tr>
</tbody>
</table>

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*
**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

- **Component alignment:**
  - < 1 mm

- **(nearly) sealed gas volume**

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

**Recent work:**
- Changed gas in pile from air to N\textsubscript{2}; eliminates $^{41}$Ar production, also ozone + nitric acid corrosion
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 ft³/minute flow of N₂ gas

Lessons learned being applied:
• Concrete is all outside the N₂ 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 N₂ 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

- Pipe is 4 m diam., 194 m long
- Static helium fill (10% more ν compared to air fill)
- Cooled by flowing 35,000 ft³/minute of nitrogen gas
- Structure dominated by concrete radiation shield
- Multiple features to keep water out

Recent work: Changed gas cooling from air to N₂, reduces ⁴¹Ar production, also corrosion

Water barriers
Fall-back water drainage
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

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

Flexible, modular design

Hadron Absorber  
Absorber Core

Ionization detectors

Muon Monitoring Alcove

Muon Shielding (steel)

Decay Pipe (4m diam.)

Beam

Sculpted Al (9)

Steel

Mask (5)

Solid Al (4)

Steel (4)
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

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

Beam focusing:
• 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 $\nu$ 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.

Target pile atmosphere and decay pipe cooling:
• Completed conceptual design for replacing air fill with nitrogen
  Eliminates production of radioactive $^{41}$Ar
  Eliminates Ozone and Nitric Acid corrosion

Target
• Developing Helium cooled target design, alternate to reference water cooled design

Beam to DUNE about a decade from now
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/cm³) in Hadron Absorber

RD  Peak: 1.6 W/cm³

OD  Peak: 0.24 W/cm³

MARS Monte Carlo