Status of the LBNF beamline

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Rutherford Appleton Laboratory

The 19th International Workshop on Neutrinos from Accelerators
25-30 September 2017
Uppsala University Main Building
LBNF = Long Baseline Neutrino Facility

Takes protons from Fermilab accelerator

Produces beam of $\nu_\mu$ or $\bar{\nu}_\mu$
Drivers for LBNF beamline design

The primary science objectives of DUNE are\cite{2}

• A comprehensive investigation of neutrino oscillations to test CP violation

\[ \nu_\mu \rightarrow \nu_e \text{ vs. } \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

• 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 \( \nu \) vs \( \bar{\nu} \) selection by beam focusing \( \pi^+ \) or \( \pi^- \)

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  
Synchrotron or linac

To Main Injector  
PIP-II has DOE CDO approval
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

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

CP violation sensitivity

Optimized system:
- Increases flux in oscillation region
- Decreases flux in high-energy tail
- Increases CP sensitivity
Beam-line Staging possibility

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

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
• 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.
Target Alternatives for 1.2MW beam

Iteration 1 (NuMI style)
- water cooled graphite fins

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

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

Replaceable target concept
Improved version of T2K target

RAL 1.2MW outline target design completed
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

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

#### Graph: Peak Energy Density in Target Material

- **T2K Design**
- **NuMI**
- **NoVA**
- **T2K Achieved**

**LBNF 1.2MW RAL design**
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-thrshld</td>
<td>144</td>
<td>151</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Neutrino power</strong></td>
<td>66</td>
<td>69</td>
<td>1.05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>2400</td>
<td>2400</td>
<td>1.05</td>
</tr>
</tbody>
</table>

For 2.4 MW proton beam power

\[ k \text{W deposited in region} \]

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

\[ 10^{-13} \text{ watt deposited in far detector!} \]

*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 $^{41}$Ar, 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)
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\textsubscript{2}
- Structure dominated by concrete radiation shielding
- Multiple features to keep water out
• 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
Summary

<table>
<thead>
<tr>
<th></th>
<th>2015 Reference design</th>
<th>2017 optimised design for DUNE physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Focusing</td>
<td>NuMI 2-horn system</td>
<td>3-horn system with longer target gives significantly improved physics performance, 2 horn staged option also on the table</td>
</tr>
<tr>
<td>Target</td>
<td>NuMI target, 1m long water cooled graphite fin target</td>
<td>Iteration 1 - 2m long 1.2MW version of NuMI target. Iteration 2 - 2m long Helium cooled graphite target</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Higher temperature operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No water hammer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Target replaceable without replacing horn</td>
</tr>
<tr>
<td>Target pile</td>
<td>Air atmosphere</td>
<td>N₂ atmosphere to deal with 41Ar. Also reduces ozone and nitric acid corrosion issues</td>
</tr>
<tr>
<td>Absorber</td>
<td>Complex sculpted absorber plates</td>
<td>Lower power absorption allows simpler design which also facilitates better muon monitoring</td>
</tr>
</tbody>
</table>

*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*