Design of the LBNE Beamline

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Outline

- LBNE Science Goals
- LBNE Project Scope
- LBNE Milestones
- Recent Beamline Scope Changes
- Beamline Design Overview
- Conclusions
LBNE Science Goals

LBNE is a comprehensive program to:

• **Measure neutrino oscillations**
  - Direct determination of CP violation in the leptonic sector
  - Measurement of the CP phase $\delta$
  - Determination of the neutrino mass hierarchy
  - Determination of the $\theta_{23}$ octant and other precision measurements
  - Testing the 3-flavor mixing paradigm
  - Precision measurements of neutrino interactions with matter
  - Searching for new physics

• **Study other fundamental physics enabled by a massive, underground detector**
  - Search for nucleon decays
  - Measurement of neutrinos from core collapse supernovae
  - Measurements with atmospheric neutrinos

The Near Detector will enable as well a broad range of precision neutrino-interaction measurements
Importance of LBNE Science

The LBNE science has been recognized to be top priority:

• Report of the Snowmass 2013 summer study
• European strategy for Particle Physics (update of 2013)
• P5 report, May 2014

The Science Drivers:
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

P5 Report, May 2014
Neutrino Program at Fermilab

**MINERvA**
- MiniBooNE
- MINOS (far)
- MINOS (near)
- Operating since 2005 (up to 375 kW)

**NOvA**
- Online in 2014 (designed for 700 kW)
- NOvA (far)
- NOvA (near)

**MicroBooNE (LAr TPC)**
- Starts commissioning in July 2014

**LBNE**
- Under development
- 1300 km
- New Neutrino Beam at Fermilab and a precision Near Detector

**SBN Program under development**
- MINOS (near)
- MINERVA
- 735 km
- 810 km

**Far detector (LAr TPC) at the Sanford Underground Research Facility (SURF)**

**MicroBooNE (LAr TPC)**
- Starts commissioning in July 2014
Evolving Scope of the LBNE Project

• LBNE is developing as an international partnership, with the goal of delivering an initial project consisting of:
  - A neutrino beamline, operating initially at 1.2 MW,
  - A highly-capable near detector system,
  - A ≥10 kt fiducial mass far detector underground at SURF, 4850 ft deep
  - Conventional facilities including a cavern at the far site for a ≥ 35 kt fiducial mass far detector system.
  - The designs of the near and far detectors and of the beam will incorporate concepts from new partners.

• The planned project allows for future upgrades:
  - The beamline is designed to be upgradeable up to 2.3 MW proton beam power.
  - Future far detector module(s) can be installed in the underground cavern.
LBNE Milestones (in May 2014 schedule)

- Critical Decision-0 (CD-0) approved, January 8, 2010.
- Office of Science in DOE asking that LBNE is staged (19 Mar. 2012).
- A three month “Reconfiguration” process and recommendation for a phased LBNE (Aug. 6, 2012).
- Successful Director’s Review of the Phase 1 LBNE Project (25-27 Sep. 2012).
- Successful DOE CD-1 Independent Project/Cost Reviews (Oct./Nov., 2012).
- CD-3a expected in October 2015. (pre-load embankment)
- CD-2 expected in January 2017 (baselining).
- CD-3b expected in October 2017.
- CD-4 expected in May 2024.

Technically driven schedule has been prepared and will be adjusted on the basis of funding

V. Papadimitriou – June 17, 2014
LBNE Beamline Reference Design: MI-10 Extraction, Shallow Beam

Beamline Facility contained within Fermilab property

- Antiproton Source
- Tevatron
- Main Injector

Kirk Rd

~ 21,370 m²
Beamline Requirements driven by the physics

• The driving **physics considerations** for the LBNE Beamline are the long-baseline neutrino oscillation analyses.
• Wide band, sign selected beam to cover the 1\textsuperscript{st} and 2\textsuperscript{nd} oscillation maxima. Optimizing for $E_{\nu}$ in the range $0.5 – 5.0$ GeV.
• The primary beam designed to transport high intensity protons in the energy range of 60-120 GeV to the LBNE target.

![Diagram of Normal mass hierarchy with CP effects and mass hierarchy peaks at 0.8 GeV and 2.4 GeV](image)

V. Papadimitriou – June 17, 2014
We have been planning so far to start with a 700 kW beam (NuMI/NOvA at 120 GeV) and then be prepared to take significantly increased beam power (~2.3 MW) allowing for an upgradeability of the facility when more beam power becomes available.

Fermilab is now planning to raise the beam power to 1.2 MW by the time LBNE starts operation (PIP-II).

- We are currently assuming operation of the Beamline for the first 5 years at 1.2 MW and for 15 years at 2.3 MW.

Stringent limits on radiological protection of environment, members of public and workers.

The lifetime of the Beamline Facility including the shielding is assumed to be 30 years.
Recent scope changes/challenges

• Be ready for **1.2 MW** at day one (**changes required in many components of the neutrino beamline**).

• **Helium** instead of air in the decay pipe to increase the neutrino flux and reduce the systematics (**an upstream decay pipe window is required and more sophisticated air cooling**).

• The helium in the decay pipe makes the design of the hadron absorber more challenging. We had to reduce temperatures and increase the safety factor even with air in the decay pipe.

• Understanding corrosion better for the decay pipe, target chase and absorber cooling lines.
  – Beamline corrosion working group
  – Corrosion consultant
  – Consulting with CERN and other HEP facilities
Proton Improvement Plan-II
Performance Goals

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Beam Energy</td>
<td>800 MeV</td>
</tr>
<tr>
<td>Linac Beam Current</td>
<td>2 mA</td>
</tr>
<tr>
<td>Linac Beam Pulse Length</td>
<td>0.6 msec</td>
</tr>
<tr>
<td>Linac Pulse Repetition Rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Linac Upgrade Potential</td>
<td>CW</td>
</tr>
<tr>
<td>Booster Protons per Pulse</td>
<td>6.4x10^{12}</td>
</tr>
<tr>
<td>Booster Pulse Repetition Rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Booster Beam Power @ 8 GeV</td>
<td>120 kW</td>
</tr>
<tr>
<td>8 GeV Beam Power to LBNE</td>
<td>80-120* kW</td>
</tr>
<tr>
<td>Beam Power to 8 GeV Program</td>
<td>40-0* kW</td>
</tr>
<tr>
<td>Main Injector Protons per Pulse</td>
<td>7.5x10^{13}</td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 120 GeV</td>
<td>1.2 sec</td>
</tr>
<tr>
<td>Main Injector Cycle Time @ 60 GeV - 80 GeV</td>
<td>0.8 sec</td>
</tr>
<tr>
<td>LBNE Beam Power @ 60 GeV</td>
<td>0.9 MW</td>
</tr>
<tr>
<td>LBNE Beam Power @ 120 GeV</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>LBNE Upgrade Potential @ 60-120 GeV</td>
<td>&gt;2 MW</td>
</tr>
</tbody>
</table>

*First number refers to Main Injector operations at 120 GeV; second number to 60 GeV. The PIP-II configuration is capable of maintaining 1.2 MW down to 80 GeV.

Pulse duration: 10 μs
Proton Improvement Plan-IV
Performance Goals

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Intensity (1e13)</th>
<th>Cycle Time (sec)</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>15</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>110</td>
<td>15</td>
<td>1.1</td>
<td>2.4</td>
</tr>
<tr>
<td>100</td>
<td>15</td>
<td>1.05</td>
<td>2.29</td>
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<tr>
<td>90</td>
<td>15</td>
<td>0.95</td>
<td>2.13</td>
</tr>
<tr>
<td>80</td>
<td>15</td>
<td>0.9</td>
<td>2.13</td>
</tr>
<tr>
<td>70</td>
<td>15</td>
<td>0.8</td>
<td>2.1</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>0.7</td>
<td>2.06</td>
</tr>
<tr>
<td>50</td>
<td>15</td>
<td>0.65</td>
<td>1.85</td>
</tr>
<tr>
<td>40</td>
<td>15</td>
<td>0.55</td>
<td>1.75</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>0.45</td>
<td>1.6</td>
</tr>
</tbody>
</table>

P. Derwent, S. Holmes, I. Kourbanis, V. Lebedev

http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1295

Building on:

http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232
Primary Beam and Lattice Functions

- The LBNE Primary Beam will transport 60 - 120 GeV protons from MI-10 to the LBNE target to create a neutrino beam. The beam lattice points to 79 conventional magnets (25 dipoles, 21 quadrupoles, 23 correctors, 6 kickers, 3 Lambertsons and 1 C magnet).

Beam size at target tunable between 1.0-4.0 mm

Horizontal (solid) and vertical (dashed) lattice functions of the LBNE transfer line

The final focus is tuned for $\sigma_x = \sigma_y = 1.50$ mm at 120 GeV/c with $\beta^* = 86.33$ m and nominal MI beam parameters $\varepsilon_{99} = 30\pi$ $\mu$m & $\Delta p_{99}/p = 11 \times 10^{-4}$

- MI-10 laser scan
- 3D model

STRUCT/MARS simulations have shown that highest beam loss rate takes place right at the apex of beamline
Primary Beam Instrumentation

- Beam-Position Monitors, Beam-Loss Monitors, Total-Loss Monitors, Beam-Intensity Monitors, Beam-Profile Monitors
  - Prototype Beam Position Monitors (already operational in NuMI). Getting simultaneously x and y information.

Button BPM operational in NuMI

Estimated BPM Resolution (1000 pulses)

Hor. & Vert. BPM resolution in μm of the NuMI split tube BPMs and the button style prototype LBNE BPM extracted from a 2-D fit

BPM # along the NuMI primary line from US to DS

~10”
Major Components of the Neutrino Beam

The neutrino spectrum is determined by the geometry of the target, the focusing horns and the decay pipe geometry.

NuMI-like low energy target & NuMI design horns with some modifications for 1.2 MW operation

Tunable neutrino energy spectrum
Target Hall/Decay Pipe Layout

**Target Chase**: 1.6 m/1.4 m wide, 24.3 m long

- **Geomembrane barrier**/draining system to keep groundwater out of decay region, target chase and absorber hall
- Considering a 250 m long Decay Pipe
- Decay Pipe concrete shielding (5.5 m)
- Baffle/Target Carrier
- Steel
- Cooling panels
- Work Cell

V. Papadimitriou – June 17, 2014
LBNE Target Design for 700 kW (CD-1)

- Developed from the NuMI Low-Energy Target
  - Same overall geometry and material (POCO Graphite)
- **Key change 1**: Cooling lines made from continuous titanium tubing instead of stainless steel with welded junctions
- **Key change 2**: Outer containment can be made out of beryllium alloy instead of aluminum
  - Be generates less heat load and is stronger at higher temperatures
  - An all Be construction eliminates brazing joint to the DS Be window
  - Titanium alloys also being investigated

- Expect to change target ~twice a year for 700 kW operation
  - Limited lifetime due to radiation damage of graphite
  - Annealing? (subject of RADIATE R&D)
- Option remains for Be as target material pending validation.
  - Radiation damage a factor of 10 less than graphite (subject of RADIATE R&D)

47 graphite segments, each 2 cm long
- Concentric Decay Pipe. Both pipes are ½” thick carbon steel.
- Decay pipe cooling air supply flows in four, 28-inch diam. pipes and the annular gap is the return path (purple flow path).
- The helium-filled decay pipe requires that a replaceable, thin, metallic window be added on the upstream end of the decay pipe.
The Absorber is designed for 2.3 MW

A specially designed pile of aluminum, steel and concrete blocks, some of them water cooled which must contain the energy of the particles that exit the Decay Pipe.

Thermal, structural, mechanical engineering development in progress

Decay Pipe
CCSS Steel
Steel
Concrete
Hadron Monitor (HM)
Remote Handling Facility for HM
Absorber design

Al core temperatures reduced significantly since November 2013 (were about 170°C)

Introducing one to three Al spoilers, thinner or sculpted blocks, different number & location of cooling lines, different water temperatures, different water flow rates...

Power density distribution

Block 4, 4 water lines (30cm/50cm), 3 spoilers, 20 gpm flow rate

Max Temp 126°C
Absorber Design/MARS Simulations (single spoiler)

Thin (12.5 cm) Al blocks

Sculpted Al blocks

Max Temp 85°C

Max Temp 90°C
Absorber Design

Aluminum core gun drilled holes
What will need to be re-evaluated or replaced at 1.2 MW
Increased collaboration opportunities

- Primary beam window
- Baffle and target, and their carrier
- Horns
- Horn power supply (we were using the NuMI one)
- Horn stripline
- Cooling panels for target chase
- Water cooling at the bottom of support modules for target/baffle and horns
- Upstream decay pipe window in the Helium filled decay pipe
- Raw systems (Target, Horns, Cooling Chase Panels, Absorber, Decay Pipe windows)
- Chillers for air handling and RAW Water systems
- Water evaporators
- Hadron Monitor
- Additional interlock system in the Absorber Hall (on top of thermocouples) to protect from primary beam accident
- Target chase shielding roof thickness
- Radioactive air releases
Sequence of work needed for designing for 1.2 MW

Primary beam window

Target chase cooling panels

Horn 1

Target

Horn 2

Horns

Power Supply

Baffle

Stripline

US and DS decay pipe windows

Baffle and Target carrier

MARS & ANSYS SIMULATIONS NECESSARY

Target chase shielding roof thickness

Done

Done

Will use pre-reconfiguration design

We are here 80% Done

80% Done

Done
1.2 MW Target/Horn Considerations

- When LBNE was reconfigured in 2012, in order to save money we abandoned our LBNE optimized target and horn designs and opted for NuMI designs with small modifications. (e.g. we were able to verify the NuMI horns up to 230 kA instead of their 200 kA design value).

<table>
<thead>
<tr>
<th></th>
<th>LBNE Sept. 2012</th>
<th>LBNE March 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Power</td>
<td>708 kW</td>
<td>708 kW</td>
</tr>
<tr>
<td>Horn 1 shape</td>
<td>Double Parabolic</td>
<td>Cylindrical/Parabolic</td>
</tr>
<tr>
<td>Horn current</td>
<td>200 kA</td>
<td>300 kA</td>
</tr>
<tr>
<td>Target</td>
<td>Modified MINOS (fins)</td>
<td>IHEP cylindrical</td>
</tr>
<tr>
<td>Target “Carrier”</td>
<td>NuMI-style baffle/ target carrier</td>
<td>New handler, target attaches to Horn 1</td>
</tr>
</tbody>
</table>

~ 25% less flux on the 2\textsuperscript{nd} oscillation max.
~ 3% more flux on the 1\textsuperscript{st} oscillation max.
1.2 MW Target/Horn Considerations

• Our current plan is to check if modest modifications to the CD-1 (NuMI-like) designs can get us to 1.2 MW, minimizing the redesign effort and the increase in cost. (Targets and horns are consumables).

• As a first attempt reduce stress by increasing beam spot size. Use NuMI target as a base but increase the fin width to 10mm and beam sigmas to 1.7mm.

• For the horns try to reduce the joule heating to make room for more beam heating (shorter pulse – cannot use the NuMI power supply).
Preliminary target design for 1.2 MW

We are simulating this target design and the NuMI horns with MARS and GEANT. It will take a couple more iterations but we see no show stoppers for this design to work.

47 graphite segments, each 2 cm long

Graphite fin stress

Water line stress

V. Papadimitriou – June 17, 2014
Preliminary target design for 1.2 MW

<table>
<thead>
<tr>
<th>Location</th>
<th>Material</th>
<th>Stress</th>
<th>Criteria</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst Case Fin</td>
<td>Graphite</td>
<td>10.5 MPa</td>
<td>UTS - 80MPa</td>
<td>7.6</td>
</tr>
<tr>
<td>Fin, Off-Center Pulse</td>
<td>Graphite</td>
<td>10.1 MPa</td>
<td>UTS - 80MPa</td>
<td>7.9</td>
</tr>
<tr>
<td>Water Line, Static</td>
<td>Ti grade 2</td>
<td>83 MPa</td>
<td>Fatigue - 270MPa @ 1e5 cycles, 150C</td>
<td>3.3</td>
</tr>
<tr>
<td>Water Line, Pulsed</td>
<td>Ti grade 2</td>
<td>M-126MPa, Alt- 32MPa</td>
<td>Goodman @ 90C (mean temp)</td>
<td>2.4</td>
</tr>
<tr>
<td>Can</td>
<td>Beryllium</td>
<td>25.9 MPa</td>
<td>Yield - 218 MPa @ 185C</td>
<td>8.4</td>
</tr>
<tr>
<td>Window</td>
<td>Beryllium</td>
<td>27.2 MPa</td>
<td>Yield - 218 MPa @ 185C</td>
<td>8.0</td>
</tr>
</tbody>
</table>

UK/RAL interested in collaborating on the target design (in addition to R&D)
Horn Operation at 1.2MW

- Beam heating and joule heating on horn 1 generate unacceptable power input into the horn inner conductor with the new target design and the NuMI horn power supply (2.1ms pulse width).

- Higher energy depositions from the target can be offset by reducing the current pulse width to 0.8ms (requires a new horn power supply).

- These changes allow the design current to remain at 230kA which is the upper current limit for a NuMI conductor design.
Horn Current Analysis Results

- Two common high stress areas are the Neck and U.S. Weld.
- There are fabrication steps and geometrical changes that can regain lost strength due to higher loading.

### Temperatures

<table>
<thead>
<tr>
<th></th>
<th>700 kW</th>
<th>1.2 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>61 C</td>
<td>77.5 C</td>
</tr>
<tr>
<td>Minimum</td>
<td>37 C</td>
<td>44.5 C</td>
</tr>
<tr>
<td>△T C</td>
<td>24 C</td>
<td>32 C</td>
</tr>
<tr>
<td>Average (Steady State)</td>
<td>48 C</td>
<td>59.4 C</td>
</tr>
</tbody>
</table>

- Increase in temperature range contributes to an increase in stresses.
- These higher stresses affect the Safety Factor (S.F.) of the horn.

### Stress Location

<table>
<thead>
<tr>
<th>Stress Location</th>
<th>700 kW Safety Factor</th>
<th>1.2 MW Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck</td>
<td>3.55</td>
<td>2.78</td>
</tr>
<tr>
<td>Downstream Weld</td>
<td>6.74</td>
<td>4.94</td>
</tr>
<tr>
<td>Upstream Weld</td>
<td>3.20</td>
<td>2.59</td>
</tr>
<tr>
<td>Upstream Transition</td>
<td>5.92</td>
<td>6.12</td>
</tr>
</tbody>
</table>

S. F. of 3 is a good goal

V. Papadimitriou – June 17, 2014
1.2 MW Target/Horn Considerations (Simulations)

A lot of simulation effort needed
Energy Depositions, radiological: MARS
Physics oriented Beamline optimization: GEANT (MARS cross check)

Increasing the horn current from 200 kA to 230 kA almost cancels the reduction of flux due to retracted target.
1.2 MW Target/Horn Considerations (Simulations)

A lot of simulation effort needed
Energy Depositions, radiological: MARS
Physics oriented Beamline optimization: GEANT (MARS cross check)

Retrack target by 10 cm
Considered design changes that increase the physics potential

<table>
<thead>
<tr>
<th>Change</th>
<th>0.5-2.0 GeV</th>
<th>2.0-5.0 GeV</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK pipe Air → He *</td>
<td>1.07</td>
<td>1.11</td>
<td>~$ 9 M</td>
</tr>
<tr>
<td>DK pipe length 200 m → 250 m (4m D)</td>
<td>1.04</td>
<td>1.12</td>
<td>~$ 30 M</td>
</tr>
<tr>
<td>DK pipe diameter 4 m → 6 m (200m L)</td>
<td>1.06</td>
<td>1.02</td>
<td>~ $17 M</td>
</tr>
<tr>
<td>Horn current 200 kA → 230 kA</td>
<td>1.00</td>
<td>1.12</td>
<td>small</td>
</tr>
<tr>
<td>Proton beam 120 → 80 GeV, 700 kW</td>
<td>1.14</td>
<td>1.05</td>
<td>Programmatic impact</td>
</tr>
<tr>
<td>Target graphite fins → Be fins</td>
<td>1.03</td>
<td>1.02</td>
<td>Increase target lifetime</td>
</tr>
<tr>
<td>Total</td>
<td>1.39</td>
<td>1.52</td>
<td></td>
</tr>
</tbody>
</table>

- Simplifies the handling of systematics as well
- Recently approved

If both $55 M
Conclusions

• Significant progress with preliminary design effort in many Beamline systems including systems that have to accommodate new scope.

• Lots of opportunities for collaboration on the design of specific Beamline components as well as on beam simulations and R&D efforts.

• We are excited and looking forward to design and build this Beamline working together with all our international partners!!
BACKUP
R&D needs (beyond engineering design)

• At 1.2 MW R&D will be needed on:
  – target (materials) – assuming minimal modifications will work
  – horns (2nd generation) – assuming minimal modifications will work
    (Optimization of 2nd generation target/horn configuration to increase flux at the 2nd oscillation max)
  – hadron monitor

• At 2.3 MW additional R&D will be needed on:
  – target (materials, shape, cooling,…)
  – horns
  – hadron monitor
  – primary beam window (only cooling aspects affected by 1.2 MW)
  – Possible impacts on Conventional Facilities
High power target materials R&D

addresses radiation damage in several high power target candidate materials aiming to determine useful lifetimes (includes graphite and beryllium)

High Intensity Beam Single Pulse Test @ CERN’s HiRadMat Facility

explore the onset of failure modes (crack initiation, fracture) of various beryllium grades/forms exposed to a high intensity, highly focused beam at the CERN SPS
LBNE Collaboration

505 (379 US + 126 non-US) members,
88 (54 US + 34 non-US institutions), 8 countries

Since December 2012:
- Collaboration has increase in size by more 40%
- Non-US fraction more than doubled
What is being designed for 2.3 MW

• Designed for **2.3 MW**, to allow for an upgrade in a cost efficient manner:
  – Primary beamline
  – the radiological shielding of enclosures (primary beam enclosure, the target shield pile and target hall except from the roof of the target hall, the decay pipe shielding and the absorber hall) and size of enclosures
  – beam absorber
  – decay pipe cooling
  – remote handling
  – radioactive water system piping (in penetrations)
Core borings completed for the LBNE Beamline
Beam Envelopes & Magnet Apertures

Dipole apertures, shown in blue, include the effects of sagitta & rolls.

Quadrupole apertures are red.

- The 99% envelopes (dashed) represent nominal MI beam parameters
  \[ \varepsilon_{99} = 30\pi \, \mu \text{m} \, \text{&} \, \Delta p_{99}/p = 11.e-4 \];

- The 100% envelopes (solid) correspond to the MI admittance at transition.
  \[ \varepsilon_{100} = 360\pi \, \mu \text{m} \, \text{&} \, \Delta p_{100}/p = 28.e-4 (\gamma_t = 21.600) \]

The beamline can transport, without losses, the worst quality beam that the MI could conceivably spew forth.
Neutrino Target Facility Comparison

- NuMI (FNAL)
- CNGS (CERN)
- NOVA (FNAL)
- T2K (J-PARC)
- LBNE - 1.2 MW (FNAL)
- LBNE - 2.4 MW (FNAL)
- SNS (ORNL) for reference

Blue – Design Beam Power
Green – Actual Beam Power

from P. Hurh
Thermal Shock in FNAL Neutrino Program

from P. Hurh
Pre-reconfiguration design of the target system with double layer cooling (Accord with IHEP/Protvino)


Target material: POCO ZXF-50 graphite

Radial thickness (mm)

<table>
<thead>
<tr>
<th>Radial Layer</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IHEP design</td>
<td></td>
</tr>
<tr>
<td>7.65</td>
<td>graphite</td>
</tr>
<tr>
<td>0.3</td>
<td>stainless</td>
</tr>
<tr>
<td>1.7</td>
<td>water</td>
</tr>
<tr>
<td>0.3</td>
<td>stainless</td>
</tr>
<tr>
<td>2.2</td>
<td>water</td>
</tr>
<tr>
<td>0.3</td>
<td>stainless</td>
</tr>
<tr>
<td><strong>12.45</strong></td>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

A row of 15.3 mm diameter and 25 mm length graphite segments separated by 0.2 mm gaps.

Alternatives: Other graphites, C-C composite, HBN, Be, etc.
Target Samples from BLIP test

- Peak integrated flux about $5.9 \times 10^{20}$ proton/cm$^2$
- Average over 1 sigma area about $4.6 \times 10^{20}$ proton/cm$^2$
- ~150 tensile samples tested

The HBN samples lost a lot of mass (30-50)% and were very weak and brittle.
Comparison of change in coefficient of thermal expansion (20-300°C) for graphite samples during two consecutive thermal cycles after irradiation. Open symbols: first cycle; Filled symbols: second cycle

R7650 graphite shows the smallest negative change in CTE before annealing but all graphites exhibit a 10% higher CTE after annealing.

In February 2013 the final report (LBNE doc 5724) was completed. The studies confirmed that out of the seven materials tested, the LBNE default target material (POCO ZXF-5Q graphite) is the best choice on the basis of strength and coefficient of expansion after irradiation. Also promising was the Toyo Tanso IG-430 graphite used in the second T2K target. A Carbon-Carbon composite material (3D weave) was partially tested and looks promising as well.
ZXF5Q Graphite core degradation

**NT-02**

10% - 15% $\nu$ decrease over 6.1e20 POT

*radiation damage? (~ 1 DPA)*

or oxidation, or ... ?

plan to autopsy next year

**NT-03**

No indication of degradation over 1.8e20 POT


**NT-07**

No indication of degradation over 2.6e20 POT

Why does later graphite appear more robust?
Current Target R&D the project is involved in and partially supports

- **Be work**: postdoc started in January 2014 at Oxford. Stage 1 literature study final report complete and delivered. Material characterization of unirradiated Be is starting. *(RADIATE)*

- **Beryllium fin test**: radiation damage studies that were proposed for ANU/NOvA (3 fins out of 50) were approved. Thermal contact test completed. Ready to install.

- **Beryllium thermal shock testing** at CERN’s HiRadMat Facility expected in January-February 2015. Oxford materials team integrated. Will use advanced microscopy to characterize material before and after beam test.

- **Graphite**: A new electrical resistivity testing fixture was designed and is being manufactured. *(RADIATE)* ———
  thermal conductivity
High Intensity Beam Single Pulse Test at CERN’s HiRadMat Facility

Planning to do single pulse beam tests on Be (and possibly other materials) for application to targets and beam windows

- Proton beam capabilities:
  - up to $4.9 \times 10^{13}$ ppp
  - 440 GeV
  - 0.1 mm – 2.0 mm sigma radius

- Test on Be windows/targets to detect:
  - Onset of plastic deformation (Diff. Image. Corl., strain gauge)
  - Fracture (DIC, leak detection, high speed camera)
  - Effect of mis-steered beam (DIC, strain gauge, leak detection)
  - Beam induced resonance (Strain gauge, LDV, High speed camera)

- May also use previously irradiated Be
Current Concept for Replaceable Decay Pipe Window

- Shows functional details only - screw drive actuator will be incorporated in top plate and driven with module-thru rods
- Water cooling plates not shown
- Most hardware anodized aluminum
- Utilizes Helicoflex Seal
Decay Pipe Cross Section – Reference Design
• Outer barrier layer constructed with industry standard methods
• Independent inner and outer barrier layers
• Minimizes potential for through-going defect
• We look towards combining features from both the Reference and Alternate designs.
Aerial View of LBNE Trajectory
Near Neutrino Detector

- Proposed by collaborators from the Indian institutions
- High precision straw-tube tracker with embedded high-pressure argon gas targets
- $4\pi$ electromagnetic calorimeter and muon identification systems
- Large-aperture dipole magnet
Based on the ICARUS design

Actual detector design will evolve with input from new partners, and may involve multiple modules of different designs.

GOAL: ≥35 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass: ~50,000 tonnes