LBNE 2+ MW TARGET R&D OVERVIEW FOR HB 2010

P. Hurh FNAL 9/30/10
Neutrino beam to DUSEL, South Dakota
THE NEUTRINO BEAM FACILITY AT FERMILAB

- Allow NUMI/MINERVA/NOvA running with LBNE
- Maximize distance between target and Near Detector

Start with a 700 kW beam. Upgradeable to > 2.0 MW.

Primary beam energy (protons from the Main Injector) from 60 to 120 GeV

LBNE Primary Beam ~ 1/6 of Main Injector

48 degree hor. bend to point to SD

~400 ft underground
~250 ft underground
~150 ft underground

250 meters long
DECAY TUNNEL

TARGET FACILITIES ~150 ft underground

NUMI TUNNEL
GIESE ROAD SUBSTATION
MI-8 SERV. BLDG.
MI-64 SERVICE BUILDING
MAIN INJECTOR COOLING POND
EXTRACTION ENCLOSURE
8 GeV ENCLOSURE
WELL # 20
MAIN RING COOLING PONDS
F3
F27
F2
F-17
Scientific Booster (Sci-BooNE)
MINI-BooNE
MI-65
MI-64
F-10
AP10
AP80
ANTIPROTON SOURCE
MAIN  INJECTOR
8 GeV ENCLOSURE
Focus of this Presentation

- Graphite target material (LBNE target IHEP conceptual design for 2 MW and baseline design for 700 kW)
  - Autopsy of NuMI Target NT-02 (FNAL)
  - Irradiation Damage Testing at BLIP (BNL, N. Simos)
- Beryllium target material (alternative LBNE target design for 2.3 MW)
  - Physics, Thermal, Structural Simulation Studies (RAL, C. Densham, et al.)
  - Correlation of predicted single pulse stress failure with empirical evidence (FNAL)
Graphite R&D

- Why Graphite?
  - Excellent for thermal shock effects (lower Cp, lower CTE, very low E, high strength at high temperatures)
  - Not toxic
  - Not dual-use technology (not export controlled)
  - Readily available (inexpensively) in many grades and forms

- Why not Graphite?
  - Rapid oxidation at high temperatures
  - Radiation damage
Graphite R&D: Radiation Damage

- Rapid degradation of properties at relatively low levels of DPA
- Evidence of complete structural failure at $1 \times 10^{21}$ p/cm$^2$ (BLIP test)
Graphite R&D: Autopsy of NuMI Target NT-02

Decrease as expected when decay pipe changed from vacuum to helium fill
No change when horn 1 was replaced
No change when horn 2 was replaced

Replacement of NT-02 with NT-03 restored yield to expected levels

Events per 1e16 POT

Reco $E_{\nu}$ (GeV)

First $\sim 4.5e20$ of $6.1e20$ POT on NT-02 shown on this plot

P. Hurh: LBNE Target R&D Overview for HB 2010 9/30/10
Graphite R&D: Autopsy of NuMI Target NT-02

- Must remove sheath to see graphite fins within
- Work cell to accomplish this autopsy is not yet available at FNAL (being built)
- Autopsy planned, but not performed yet (pictures are prior to installation)
Graphite R&D: Autopsy of NuMI Target NT-02

- Work Cell at the new C-0 Remote Handling Facility is under construction
- Will have lead glass window, internal crane, manipulators, and shielding to work on items up to 1,000 R/hr
- Hope to complete in late Fall 2010
Graphite R&D:
Irradiation Testing at BLIP

- Working with N. Simos and H. Kirk at BNL to test samples irradiated by 181 MeV proton beam at BLIP
- Testing for:
  - Tensile properties (YS, UTS, …)
  - Coef. of thermal expansion
  - Thermal (electrical) conductivity
- Most samples encapsulated in argon filled, stainless steel capsules to isolate from water cooling bath
- About 150 samples in total

Tensile samples have gauge width of 3 mm and thickness of 1 mm
Graphite R&D: Irradiation Testing at BLIP

<table>
<thead>
<tr>
<th>Material</th>
<th># Tensile</th>
<th># CTE</th>
<th>K</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-C Comp (3D)</td>
<td>10</td>
<td>8</td>
<td>?</td>
<td>First BLIP test showed massive failure</td>
</tr>
<tr>
<td>POCO ZXF-5Q</td>
<td>21</td>
<td>6</td>
<td>.46</td>
<td>NuMI/NOvA target material</td>
</tr>
<tr>
<td>Toyo-Tanso IG 430</td>
<td>42</td>
<td>6</td>
<td>.51</td>
<td>“Nuclear Grade” planned for T2K</td>
</tr>
<tr>
<td>Carbone-Lorraine 2020</td>
<td>21</td>
<td>6</td>
<td>.60</td>
<td>CNGS target material</td>
</tr>
<tr>
<td>SGL R7650</td>
<td>21</td>
<td>6</td>
<td>.66</td>
<td>NuMI/NOvA Baffle material</td>
</tr>
<tr>
<td>Saint-Gobain AX05 hBN</td>
<td>0</td>
<td>6</td>
<td>.80</td>
<td>Highest K wild card (low flex strength)</td>
</tr>
</tbody>
</table>

- K Factor is a thermal shock resistance parameter used by Luca Bruno to evaluate candidate materials for targets/windows
- \( K = \frac{UTS \cdot Cp}{E \cdot CTE} \)
Graphite R&D: Irradiation Testing at BLIP

- Irradiation run complete
- Currently beginning testing phase
- Preliminary results in October, 2010

- 181 MeV proton beam
- 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$^2$
Graphite R&D: Irradiation Testing at BLIP

- Water immersed c-c samples showed structural damage (as before).
Graphite radiation damage issues prompted LBNE to look at Beryllium as an alternative target material for 2+ MW proton beam power.

Accord with (STFC) RAL’s Target Engineering Group

- Beryllium target simulations at 2+ MW
- Integrated Be target and horn conceptual design
- Cooling technology R&D (gas, water, water spray)
- Proton beam window conceptual design
- Air cooled Be target for 700 kW
Beryllium R&D:
Be Target Simulations

- Analysis encompasses:
  - Physics (FLUKA) – Energy Deposition & Figure of Merit
  - Thermal/Structural (ANSYS)
  - Dynamic/Stress-wave (Autodyne & ANSYS)
  - Off-center beam cases

- Beam Parameters:

<table>
<thead>
<tr>
<th>Proton Beam Energy (GeV)</th>
<th>Protons per Pulse</th>
<th>Repetition Period (sec)</th>
<th>Proton Beam Power (MW)</th>
<th>Beam sigma, radius (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>4.9e13</td>
<td>1.33</td>
<td>0.7</td>
<td>1.5-3.5</td>
</tr>
<tr>
<td>60</td>
<td>5.6e13</td>
<td>0.76</td>
<td>0.7</td>
<td>1.5-3.5</td>
</tr>
<tr>
<td>120</td>
<td>1.6e14</td>
<td>1.33</td>
<td>2.3</td>
<td>1.5-3.5</td>
</tr>
<tr>
<td>60</td>
<td>1.6e14</td>
<td>0.76</td>
<td>2</td>
<td>1.5-3.5</td>
</tr>
</tbody>
</table>

Pulse Length = 9.78 micro-sec
Beryllium R&D:
Be Target Simulations: FoM

- **Figure of Merit**
  - Provide simple, faster way to gauge effects of target/beam parameter changes on yield of neutrinos of interest
  - Proposed by R. Zwaska

\[
FoM = \sum_{n=1}^{21} (Ecn_n)^{2.5} \int_{E_{\text{min}}}^{E_{\text{max}}} \int_{0}^{\Delta p} \frac{\partial^2 N}{\partial E \partial p} dp \, dE
\]
Beryllium R&D:
Be Target Simulations: Structural

- Representative plot of equivalent stress
- End of Pulse
- 120 GeV, 0.7 MW beam
- 9mm radius Be
- Sy~270 MPa at 150 C
**Beryllium R&D:**

**Be Target Simulations: Structural (non-dynamic)**

<table>
<thead>
<tr>
<th>Beam Energy (GeV)</th>
<th>Beam Power (MW)</th>
<th>Beam Sigma (mm)</th>
<th>Deposited Energy (kJ/spill)</th>
<th>Time Averaged Power (kW)</th>
<th>Peak Energy Density (J/cc/spill)</th>
<th>Max. ΔT per spill (K)</th>
<th>Max. Von-Mises Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.7</td>
<td>1.5</td>
<td>4.2</td>
<td>3.2</td>
<td>254</td>
<td>76</td>
<td>100</td>
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<tr>
<td></td>
<td></td>
<td>3.5</td>
<td>9.2</td>
<td>6.9</td>
<td>74</td>
<td>22</td>
<td>27</td>
</tr>
<tr>
<td>60</td>
<td>0.7</td>
<td>1.5</td>
<td>2.9</td>
<td>3.8</td>
<td>243</td>
<td>73</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5</td>
<td>5.8</td>
<td>7.7</td>
<td>61</td>
<td>18</td>
<td>23</td>
</tr>
<tr>
<td>120</td>
<td>2.3</td>
<td>1.5</td>
<td>14.0</td>
<td>10.5</td>
<td>846</td>
<td>254</td>
<td>334</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5</td>
<td>30.7</td>
<td>23.1</td>
<td>245</td>
<td>74</td>
<td>88</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>1.5</td>
<td>8.4</td>
<td>11.1</td>
<td>707</td>
<td>212</td>
<td>288</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.5</td>
<td>17.0</td>
<td>22.3</td>
<td>176</td>
<td>53</td>
<td>68</td>
</tr>
</tbody>
</table>

Stresses probably too high for 2 MW cases with 1.5 mm beam sigma radius, but well within reason for 3.5 mm beam sigma radius

**Room for optimization!**
Beryllium R&D:
Be Target Simulations: Dynamic

- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- Compare to 88 Mpa for static case (double)
- Mainly longitudinal stress-waves
Beryllium R&D:
Be Target Simulations: Dynamic

- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- 50 mm Segments
- Peak eqv stress reduced to 109 MPa from 188 MPa
Beryllium R&D: Be Target Simulations: Off Center Beam

- 2.3 MW
- 120 GeV
- 3.5 mm sigma spot
- 2 sigma offset
- Clearance to Horn Inner Conductor is ~5mm
- Bending stress and resonance could be problem
- Target will need radial supports

P. Hurh: LBNE Target R&D Overview for HB 2010 9/30/10
Beryllium R&D:
Integrated Target Conceptual Design
Beryllium R&D: Integrated Target Conceptual Design

Software: FLUKA

Inputs:
- Proton beam parameters

Model:
- Energy Deposition (3D)
- Emag Transient (3D slice)

Outputs:
- Energy density distribution
- Magnetic field
- Current density
- Joule heating
- Lorentz force
- Temperature distribution
- Static stress / strain

ANSYS Electromagnetic

- Current pulse definition

ANSYS Thermal

- Beam heat generation rates
- Resistive heat generation rates
- Temperature distribution

ANSYS Mechanical

- Nodal temperatures
- Nodal forces

P. Hurh: LBNE Target R&D Overview for HB 2010 9/30/10
Figure 5.20, multi-pulse results, 2.3 MW beam

Table 5.4, multi-pulse results summary

<table>
<thead>
<tr>
<th>Beam Energy (GeV)</th>
<th>Beam Power (MW)</th>
<th>Beam Sigma (mm)</th>
<th>Target / Conductor Diameter (mm)</th>
<th>Peak Current (kA)</th>
<th>Current Pulse Length (milli-sec)</th>
<th>Deposited Beam Energy (kJ/Spill)</th>
<th>Deposited Resistive Energy (kJ/pulse)</th>
<th>Steady-state Power (kW)</th>
<th>Maximum Temp. 1st Cycle (K)</th>
<th>Maximum Temp. 20th Cycle (K)</th>
<th>Maximum VM-Stress 1st Cycle (MPa)</th>
<th>Maximum VM-Stress 20th Cycle (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.7</td>
<td>3.5</td>
<td>21</td>
<td>300</td>
<td>1.0</td>
<td>9.2</td>
<td>7.6</td>
<td>12.6</td>
<td>326</td>
<td>369</td>
<td>28.3</td>
<td>29.8</td>
</tr>
<tr>
<td>120</td>
<td>2.3</td>
<td>3.5</td>
<td>21</td>
<td>300</td>
<td>1.0</td>
<td>30.7</td>
<td>7.6</td>
<td>28.8</td>
<td>377</td>
<td>472</td>
<td>84.0</td>
<td>109</td>
</tr>
</tbody>
</table>
Beryllium R&D:
RAL Simulation Study Summary

- Beryllium is a viable option for 2+ MW beam
- Probably need to increase beam spot size to a sigma radius of 3 to 3.5 mm
- Segmenting the target longitudinally is beneficial
- Off center beam pulses will require mechanical supports along length of target
- Integrated target/horn design looks promising
- RAL Target Group continues working on:
  - Optimizing beam/target radius for good compromise between physics and target survivability
  - Add end effects to integrated target simulations
  - Investigating cooling technology options
  - And more…
Progress on Combined target and horn concept

Electromagnetic – Thermal – Structural modelling

- Including the horn “end bells” allows the axial Lorentz forces transmitted by the inner conductor to be captured in the simulation.

ANSYS model of the combined target / inner conductor concept.

Axial Lorentz forces induce a significant tensile stress component in the solid inner conductor.

P. Hurh: LBNE Target R&D Overview for HB 2010 9/30/10
Progress on Separate target

Drill down on dynamic stresses

Total stresses = “Quasi-steady” stresses + Dynamic stresses

“Quasi-steady” stresses
i.e. thermal gradient.
Time scale: thermal diffusivity

Dynamic stresses
i.e. reflection and resonance of stress waves within the geom.
Time scale: sound speed

Segmentation of the target minimises the dynamic components quickly resolving to the “quasi-steady” stress field

Avoiding sharp edges in the target geometry reduces both stress concentrations and constructive wave interference
Progress on Separate target continued

- **Design Selection Parameters**
  - Peak stress with off centre beam & FoM
  - Design choice
  - Diameter & Shape (Rod vs Segments)

1. Reducing target diameter gives better pion yield but more stress.
2. Beam induced dynamic stress in the form of longitudinal stress waves and from induced vibrations are significant in a beryllium rod ruling it out for 2.3MW operation.
3. Segmenting the target (a series of spheres for example) has been identified as a potential option for achieving the desired diameter with reasonable stress levels.
4. FoM is comparable between spheres and rod.
Beryllium R&D:
Failure Criteria – Simulation versus Reality

- Predicted Peak Energy Deposition for LBNE 2.3 MW with 1.5 mm beam sigma radius was 846 J/cc and thought to cause stresses too high for Be to survive.
- But P-bar Target (FNAL) has a Beryllium cover that regularly sees 1000 J/cc and shows no evidence of damage.
- ANSYS analysis for similar conditions suggests peak equivalent stresses of 300 Mpa (elastic-plastic, temp-dependent mat’l properties, but not dynamic).
- Dynamic stresses could be 30-50% higher.
Beryllium R&D:
Failure Criteria – Simulation versus Reality

- 120 GeV
- 0.2 mm sigma
- Elastic/plastic
- Temp Dependent Mat’l Properties
- Peak Seqv is 300 MPa
- Peak Temp is ~800 C
- Be Melting Temp is 1278 C
- Be UTS at 600 C is ~150 MPa
Beryllium R&D:
Failure Criteria – Simulation versus Reality

- Rotated 17 degrees every pulse
- Moved 1 mm vertically every 2e17 protons
- Typical beam sigma was 0.195 mm (last 1-2 months of running at 0.15 mm)
- Typical ppp was 8E12
- This target saw about 5e6 pulses at the time photo was taken
Possible explanations

- Small areas of deformation not visible
  - Analysis indicates about 0.05 mm of plastic deformation on surface in an outward “bump” with diameter of about 1 mm

- Beam profile is not gaussian
  - At such small sigma, peak energy deposition would be reduced greatly if profile were flat in center of beam

- Fast energy deposition rate creates high strain rates
  - Yield strength of metals increases for high strain rates
Beryllium R&D:
Failure Criteria – Simulation versus Reality

- Max strain predicted is 0.01 strain
- Pulse length is 1.6 micro-sec
- Strain rate is over 6,000 s⁻¹
- For LBNE 2.3 MW, 3.5 mm sigma, strain rate=100 s⁻¹
- For LBNE 2.3 MW, 1.5 mm sigma, strain rate=340 s⁻¹
Beryllium R&D:
Failure Criteria – Simulation versus Reality

- Yield and Ultimate Stresses increase by 25-40% at strain rates greater than 100 s$^{-1}$
- Significant increased hardening as well


Beryllium R&D:
Failure Criteria – Simulation versus Reality

- Damage seen on Be Lithium Lens Windows
- Just DS of Target
- Higher Temperature
- Higher Stress (10,000 psi of Li pressure on other side)
- Damage observed after 8 months of running at reduced spot size of 0.15 mm sigma and not at larger spot size (0.19 mm sigma)
Beryllium R&D:
Failure Criteria – Simulation versus Reality

- More work needs to be done in this area to set limits of Be in high power proton beams
  - Effects of irradiation and temperature
  - Refined simulation of actual conditions
  - In beam validation/benchmarking test

- For now, set conservative limits and push the envelope later...
Graphite target material
- Autopsy of NuMI Target NT-02 (FNAL)
- Irradiation Damage Testing at BLIP (BNL, N. Simos)

Beryllium target material
- Physics, Thermal, Structural Simulation Studies (RAL, C. Densham, et al.)
- Correlation of predicted single pulse stress failure with empirical evidence (FNAL)

Work will progress in all areas, stay tuned…
Thanks to all