Megawatt targets for Neutrino Super-Beams
(Apr. 4, 2013)

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LBNE study in collaboration with: Patrick Hurh, Bob Zwaska, James Hylen, Sam Childress, Vaia Papadimitriou (Fermilab)

+ T2K Beam Group

+ LAGUNA/LBNO/CN2PY Study Group
### ‘Conventional’ neutrino beams: where we are

<table>
<thead>
<tr>
<th></th>
<th>Fermilab NuMI/NOvA</th>
<th>JPARC T2K</th>
<th>CERN CNGS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>120 GeV</td>
<td>30 GeV</td>
<td>400 GeV</td>
</tr>
<tr>
<td><strong>Beam cycle</strong></td>
<td>2.2 s</td>
<td>2.1 s</td>
<td>6 s</td>
</tr>
<tr>
<td><strong>Spill length</strong></td>
<td>10 µs</td>
<td>4.2 µs</td>
<td>2 x 10.5 µs</td>
</tr>
<tr>
<td><strong>Design beam power</strong></td>
<td>400 kW</td>
<td>750 kW</td>
<td>750 kW</td>
</tr>
<tr>
<td><strong>Maximum beam power to date</strong></td>
<td>375 kW</td>
<td>230 kW</td>
<td>311 kW (448 kW over 30s)</td>
</tr>
<tr>
<td><strong>Beam size (rms)</strong></td>
<td>1.1 mm</td>
<td>4.2 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td><strong>Physics</strong></td>
<td>$\nu_\mu$ disappearance</td>
<td>$\nu_\mu \rightarrow \nu_e$ appearance, $\nu_\mu$ disappearance</td>
<td>$\nu_\mu \rightarrow \nu_\tau$ appearance</td>
</tr>
<tr>
<td><strong>First beam</strong></td>
<td>2005</td>
<td>2009</td>
<td>2006</td>
</tr>
</tbody>
</table>
# Neutrino ‘Superbeams’: where we want to go

<table>
<thead>
<tr>
<th></th>
<th>Fermilab LBNE (/Project X)</th>
<th>JPARC T2K Long term plan (2018-)</th>
<th>CERN CN2PY/LBNO (Phase 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design beam power</td>
<td>2.3 MW</td>
<td>3.2 MW</td>
<td>2 MW</td>
</tr>
<tr>
<td>Beam energy</td>
<td>120 GeV</td>
<td>50 GeV</td>
<td>50 (70)GeV</td>
</tr>
<tr>
<td>Rep rate</td>
<td>0.75 Hz</td>
<td>1 Hz</td>
<td>1.33 Hz</td>
</tr>
<tr>
<td>Beam sigma (range)</td>
<td>1.5 – 3.5 mm</td>
<td>4.2 mm</td>
<td></td>
</tr>
<tr>
<td>Heat load in: C Be Ti pebble bed</td>
<td>10.5 – 23.1 kW</td>
<td>~100 kW</td>
<td></td>
</tr>
</tbody>
</table>
Neutrino Program at Fermilab

under construction
Online 2013 (700 kW)

NOvA (far)

MINOS (far)

Operating since 2005 (350 kW)

MINOS (near)

MINERvA

Near detector

LBNE under development
1300 km

810 km

735 km

Far detector
(33 kton LAr TPC)

MicroBooNE
under construction
(LAr TPC)
LBNE Target Facility - for 2.3 MW operation

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

Decay Pipe concrete shielding (5.5 m)

Decay Pipe: Length - 200 m
Radius - 2 m

Geomembrane barrier system to keep groundwater out of decay region (Target Chase & Absorber Hall also)
History of delivered beam to the T2K experiment

Accumulated number of proton $\sim 4.2 \times 10^{20}$ POT.
T2K: Plans for 8 GeV Booster Ring for 2-3 MW
CN2PY - Layout Options

Update since CERN Meeting - October'12

For the WP4 Layout Study Group:
M. Calviani, I. Efthymiopoulos, B. Goddard,
A. Kosmicki, J. Osborne, Y. Papaphilippou, R.
Steerenberg, P. Velten, H. Vincke

LLBNO Meeting, DESY February 27, 2013
Option A:
- 400 GeV extraction from TT60 (TI2)
- Target cavern close to BA2
- ND just outside Prevezzin fenced area
Preliminary Concept for CN2PY

- Keep as many buildings as possible at the surface to keep construction costs down
  - Must have a shaft to access the horns and targets
  - Power supplies (or transformers) must be underground, close to the beamline
  - The pump house may also be underground, depending on the acceptable pressure drop

*Drawings not to scale: number and layout of horns will be different in practice, as will beamline dimensions*

Dan Wilcox
**CERN ν-beam to Pyhäsalmi - CN2PY**

**CN2PY beam**

- **Phase 1**: use the proton beam extracted beam from SPS
  - 400 GeV, max $7.0 \times 10^{13}$ protons every 6 sec, 750 kW nominal beam power, 10 μs pulse

- **Phase 2**: use the proton beam from the new HP-PS
  - 50(70) GeV, 1.33 Hz, $1.9 \times 10^{14}$ ppp, 2 MW nominal beam power, 4 μs pulse

**Requirements - layout**

- Use the same secondary beam elements for both beams
  - sufficient shielding to contain the produced radiation
    - including muons, water and soil activation (H3 and NA22 production)
  - target and focusing elements (horns) with similar parameters
    - same layout or allow variations already from the design phase
    - don’t have to be identical since anyhow are to be exchangeable

- Use the same beam decay volume, dump and near detector
  - deposited energy in target, shielding and dump would be $\times 2.7$ higher for the Phase-II beam

- The facility layout is driven by the 400 GeV beam
- The target cavern layout (shielding) is driven by the 50(70) GeV beam and the 2MW of power
Target Basics (J.Hylen)

Long enough (2 interaction lengths) to interact most protons
Dense enough that 2 \( \lambda_{\text{int}} \) fits in focusing system depth-of-field
Radius: \( R_{\text{target}} = 2.3 \) to 3 \( R_{\text{beam}} \) (minimize gaussian tails missing target)
Narrow enough that pions exit the sides without re-absorption
  (but for high \( E_{\text{proton}} \) and low \( E_{\nu} \), secondary shower can help)
High pion yield (but to first order, \( \nu \) flux \( \alpha \) beam power)
  Radiation hard
  Withstand high temperature
  High strength (withstand stress from fast beam pulse)
  Low density (less energy deposition density, hence less stress; don’t re-absorb pions)
  Low \( dE/dx \) (but not much variation between materials)
  High heat capacity (less stress induced by the \( dE/dx \))
  Low thermal expansion coefficient (less stress induced by the \( dE/dx \))
  Low modulus of elasticity (less stiff material does not build up stress)
  Reasonable heat conductivity
  Reasonable electrical conductivity (monitor target by charge ejection)

\textit{CNGS, NuMI, T2K all using graphite}
# Existing target technologies

<table>
<thead>
<tr>
<th></th>
<th>NuMI/NOvA</th>
<th>CNGS</th>
<th>T2K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target material</strong></td>
<td>Graphite: POCO ZXF-5Q</td>
<td>Graphite and Carbon-carbon</td>
<td>Graphite: IG 430</td>
</tr>
<tr>
<td><strong>Target arrangement</strong></td>
<td>Subdivided</td>
<td>subdivided</td>
<td>monolithic</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Water (forced convection)</td>
<td>Helium (natural convection)</td>
<td>Helium (forced convection)</td>
</tr>
</tbody>
</table>
| **Limitations for higher power operation** | - Radiation damage  
- Water hammer, cavitation  
- Hydrogen + tritium + water activation | - Only possible for low deposited heat loads | - Heat transfer  
- Radiation damage  
- High helium volumetric flow rate (and high pressure or high pressure drops) |
Limitations of target technologies
Ashes to ashes, dust to dust...

Effect of proton beams on some graphite targets

LAMPF fluence
$10^{22} \text{ p/cm}^2$

BNL tests:
fluence $\sim 10^{21} \text{ p/cm}^2$

PSI fluence
$10^{22} \text{ p/cm}^2$
Physics vs Engineering Optimisation?
Target and Beam Dimensions

• For pion yield - smaller is better
  - Maximum production and minimum absorption (shown by FoM)

• For target lifetime - bigger is better
  - Lower power density - lower temperatures, lower stresses
  - Lower radiation damage density

• For integrated neutrino flux, need to take both neutrino flux and lifetime factors into account
  - Want to make an assessment of trade off between target lifetime vs beam and target dimensions
  - Answer will depend on Target Station engineering (time to change over target and horn systems)
1. LBNE at Fermilab
   - **Integral target and horn inner conductor**
     - Solid Be rod
     - Water spray cooled
   - Separate target installed inside bore of horn inner conductor
     - Graphite, water cooled (IHEP study (baseline))
     - Be: subdivided in z, water cooled
     - Be: spheres, helium cooled

2. EUROnu SuperBeam using high power SPL at CERN
   4-horn system (4 x 12.5 Hz)
   - ‘Pencil’ shaped beryllium rod
   - ‘Packed bed’ of titanium beads
   - Integral target and horn inner conductor
   - (Graphite excluded due to radiation damage concerns)
Effect of beam spill time on the peak dynamic stress in the target

Effect of Spill Duration on Peak Dynamic Stress in the Target
Free Beryllium Cylinder (Ø21mm L1000mm, beam-sigma = 3.5mm)
2.3MW beam power (1.6e14 protons/spill @ 120 GeV, 0.75 Hz rep-rate )
LBNE Beryllium rod target: Stress-Waves

- “static” stress component is due to thermal gradients
  - Independent of spill time

Effect of beam spill time on the peak dynamic stress in the target

- Static Stress Component = 90 MPa

Effect of spill duration on peak dynamic stress in the target

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- $T_{spill} >$ Radial period
  - Radial stress waves are not significant

Effect of beam spill time on the peak dynamic stress in the target
LBNE Beryllium rod target: Stress-Waves

- “static” stress component is due to thermal gradients
  - Independent of spill time
- “dynamic” stress component is due to stress waves
  - Spill time dependent
- T\textsubscript{spill} > Radial period
  - Radial stress waves are not significant
- T\textsubscript{spill} < Longitudinal period
  - Longitudinal stress waves are important!

Effect of beam spill time on the peak dynamic stress in the target
Pressurised helium cooled concept (2 MW)
Pressurised helium cooled concept (2 MW)

Heat transfer coefficient

Mid-plane temperatures

Otto Caretta & Tristan Davenne
Pressurised helium cooled concept (2 MW)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beryllium sphere diameter</td>
<td>13 mm</td>
</tr>
<tr>
<td>Beam sigma</td>
<td>2.2 mm</td>
</tr>
<tr>
<td>Helium mass flow rate</td>
<td>17 g/s</td>
</tr>
<tr>
<td>Inlet helium pressure</td>
<td>11.1 bar</td>
</tr>
<tr>
<td>Outlet helium pressure</td>
<td>10 bar</td>
</tr>
<tr>
<td>Inlet velocity</td>
<td>40 m/s</td>
</tr>
<tr>
<td>Maximum velocity</td>
<td>185 m/s</td>
</tr>
<tr>
<td>Total heat load</td>
<td>9.4 kW</td>
</tr>
<tr>
<td>Maximum beryllium temperature</td>
<td>178 C</td>
</tr>
<tr>
<td>Helium temperature rise, $\Delta T (T_{in}-T_{out})$</td>
<td>106 C</td>
</tr>
</tbody>
</table>
Conclusions: ‘Divide and Rule’ for increased power

Dividing material is favoured since:
- Better heat transfer
- Lower static thermal stresses
- Lower dynamic stresses from intense beam pulses

Helium cooling is favoured (cf water) since:
- No ‘water hammer’ or cavitation effects from pulsed beams
- Lower coolant activation, no radiolysis
- Negligible pion absorption – coolant can be within beam footprint
- For graphite, higher temperatures anneal radiation damage

Static, low-Z target concepts proposed
Packed Bed Target Concept Solution

Packed bed cannister in symmetrical transverse flow configuration

Titanium alloy cannister containing packed bed of titanium alloy spheres
Cannister perforated with elliptical holes graded in size along length

Model Parameters
Proton Beam Energy = 4.5 GeV
Beam sigma = 4 mm
Packed Bed radius = 12 mm
Packed Bed Length = 780 mm
Packed Bed sphere diameter = 3 mm
Packed Bed sphere material: Titanium Alloy
Coolant = Helium at 10 bar pressure
Particle bed advantages

- Large surface area for heat transfer
- Coolant can pass close to maximum energy deposition
- High heat transfer coefficients
- Low quasi static thermal stress
- Low dynamic stress (for oscillation period << beam spill time)

... and challenges

- High pressure drops, particularly for long thin superbeam target geometry
  - Need to limit gas pressure for beam windows
- Transverse flow reduces pressure drops - but
  - Difficult to get uniform temperatures and dimensional stability of container
Streamlines in packed bed

Packed bed modelled as a porous domain

Permeability and loss coefficients calculated from Ergun equation (dependant on sphere size)

Overall heat transfer coefficient accounts for sphere size, material thermal conductivity and forced convection with helium

Interfacial surface area depends on sphere size

Acts as a natural diffuser flow spreads through target easily
Titanium temperature contours

Maximum titanium temperature = 946 K = 673 °C (N.B. Melting temp = 1668 °C)

Outer Can Surface Temp

Almost Symmetric Temperature contours

Maximum surface Temperature = 426 K = 153 °C

NB windows not included in model yet

- Double skin Be should withstand both heat and pressure loads
Future LBNE Collaborative Opportunities?

• Further prototyping on **LBNE 700 kW target** (Be or Ti outer tube replacing Al)
  – Eventual manufacture of spare target?
  – Requires good design/analysis and manufacturing capabilities
• Pre-conceptual scoping of **2.3 MW target** (graphite or Be)
  – Requires good design/analysis capabilities
• Conceptual design and prototyping of **LBNE beam windows:**
  – Especially for 2+ MW beam power
  – Possibility of **Decay Pipe windows** (challenge even at 700 kW)
  – Requires good design/analysis capabilities
• **Hadron Monitor** design and prototyping (eventual manufacture?)
  – Need new radiation hardened version for LBNE
  – Requires good design/analysis and manufacturing capabilities
Hadron Monitor

- Measures position and intensity of secondary particles at the end of the decay pipe (in absorber shield pile)
- LBNE has shorter decay pipe than NuMI
  - More heating
  - More radiation damage
  - 5x better resolution
- Current conceptual design is parallel plate ionization chambers with low pressure helium
- Used during beam/target/horn alignment & diagnostic scans and monitoring degradation of target material
- Good project to take from design to construction
Target collaboration for the first Neutrino Superbeam

- Whichever facility - LBNE/LBNO/T2HK - is first to be approved for construction/upgrade to operate in the MW region, there will be little time to develop a target system
- There is very significant commonality/synergy between the target/horn system and target station for all proposed facilities
- Now is a good time to get ready by collaborating over the necessary research and development
- Common challenges/areas for collaboration:
  - Target station design (T2K already constructed for 3-4 MW)
  - Beam window
  - Low Z target, 1-3 $\lambda$ long
    - heat transfer, stress waves, lifetime - radiation damage effects, performance optimisation
  - Integration of target with horn to capture low energy pions
  - Horn - lifetime, radiation damage effects
  - Instrumentation - OTR, beam