Megawatt targets (and horn) for Neutrino Super-Beams

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

EUROnu Superbeam study in collaboration with:
Andrea Longhin, Marco Zito (CEA Saclay);
Benjamin Lepers, Christophe Bobeth, Marcos Dracos (Universite de Strasbourg)
### 'Conventional' Neutrino Beams: Where We Are

<table>
<thead>
<tr>
<th></th>
<th>NuMI (Fermilab)</th>
<th>CNGS (CERN)</th>
<th>T2K (JPARC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>120 GeV</td>
<td>400 GeV</td>
<td>30 GeV</td>
</tr>
<tr>
<td>Beam cycle</td>
<td>2.2 s</td>
<td>6 s</td>
<td>2.1 s</td>
</tr>
<tr>
<td>Spill length</td>
<td>10 μs</td>
<td>2 x 10.5 μs</td>
<td>4.2 μs</td>
</tr>
<tr>
<td>Design beam power</td>
<td>400 kW</td>
<td>750 kW</td>
<td>750 kW</td>
</tr>
<tr>
<td>Maximum beam power to date</td>
<td>375 kW</td>
<td>311 kW (448 kW over 30s)</td>
<td>135 kW</td>
</tr>
<tr>
<td>Beam size (rms)</td>
<td>1.1 mm</td>
<td>0.5 mm</td>
<td>4.2 mm</td>
</tr>
<tr>
<td>Physics</td>
<td>$\nu_\mu$ absence</td>
<td>$\nu_\mu \rightarrow \nu_\tau$ appearance</td>
<td>$\nu_\mu \rightarrow \nu_e$ appearance, $\nu_\mu$ disappearance</td>
</tr>
<tr>
<td>First beam</td>
<td>2005</td>
<td>2006</td>
<td>2009</td>
</tr>
</tbody>
</table>
NuMI MINOS target (J. Hylen)

Graphite Fin
Core
6.4 mm wide

2 int. length long; narrow so pions get out sides without re-interacting

Fits within the horn without touching.

Water cooling tube

8/29/2010
NBI2010
NUMI/NOVA/LBNE Targets
CNGS Target

13 graphite rods, each 10cm long, 
Ø = 5mm and/or 4mm
2.7mm interaction length

Ten targets (+1 prototype) have been built. → Assembled in two magazines.

7th NBI 2010, J-PARC, Japan, 28-31 Aug 2010

Edda Gschwendtner, CERN
## 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) |
# Neutrino 'Superbeams': where we want to go

<table>
<thead>
<tr>
<th></th>
<th>Fermilab LBNE (/Project X)</th>
<th>CERN: SB to Frejus using HP SPL</th>
<th>LBNO</th>
<th>JPARC T2K ‘Roadmap’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design beam power</td>
<td>2.3 MW</td>
<td>4 MW</td>
<td>2 MW</td>
<td>1.66 MW</td>
</tr>
<tr>
<td>Beam energy</td>
<td>120 GeV</td>
<td>5 GeV</td>
<td>400 GeV</td>
<td>30 (50) GeV</td>
</tr>
<tr>
<td>Rep rate</td>
<td>0.75 Hz</td>
<td>50 Hz (4 x 12.5 Hz)</td>
<td></td>
<td>0.48 Hz</td>
</tr>
<tr>
<td>Beam sigma (range)</td>
<td>1.5 - 3.5 mm</td>
<td>4 mm</td>
<td></td>
<td>4.2 mm</td>
</tr>
<tr>
<td>Heat load in: C Be Ti pebble bed</td>
<td>10.5 - 23.1 kW</td>
<td>4 x 50 kW</td>
<td></td>
<td>51.8 kW</td>
</tr>
</tbody>
</table>
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 $\propto$ 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)

*CNGS, NuMI, T2K all using graphite*
Pion yields comparable for carbon and mercury targets.

Neutron flux for Hg reduced by ~ x15 with C !!

(lower neutron flux => lower heating and radiation damage to horn)

(A. Longhin)
200 kW heat load in graphite = 10 x T2K heat load at 750 kW
LBNE optimisation of Target and Beam dimensions: a simple ‘Figure of Merit’

- Target performance evaluated using FLUKA to generate a simple ‘Figure of Merit’
- ‘FoM’ is convolution of selected pion energy histogram by a weighting function:
  - \( W(E) = E^{2.5} \)
    for
    - \( 1.5 \text{ GeV} < E < 12 \text{ GeV} \)
    - \( p_T < 0.4 \text{ GeV/c} \)
- Weighting function compensates for low abundance of most useful (higher energy) pions
- Devised by R. Zwaska (FNAL)
- Implemented in FLUKA by Tristan Davenne

**Diagram:**

![Graph showing yield in energy range of interest vs. pion energy. The total yield is 1.43 pions/proton.](image)
Change in FoM with target radius

FoM [pions+/proton * GeV^2.5]

target radius [mm]

Change in FoM with target radius
beam sigma=3.5mm
beam sigma=1.5mm
large target design radius = 3sigma
small target design radius = 3sigma

Tristan Davenne
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)
Target configurations considered for Superbeams

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)

3. Other ideas
   - Fluidised bed for ultra-high powers
LBNE: Combined target and horn inner conductor?
Magnetic modelling

Longitudinal force in inner conductor

\[ F_{\text{long}} = \frac{\mu_0 I^2}{4\pi} \ln \left( \frac{R_2}{R_1} \right) \]
Solid beryllium inner conductor diameter = 21mm

Max current density: 1200 A/mm²

Max. Lorentz stress: 129 MPa

Max. magnetic field: 5.6 Tesla

Max. temperature: 311 K
Effect of spill duration on the 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)

Effect of beam spill time on the peak dynamic stress in the target
• “static” stress component is due to thermal gradients
  - Independent of spill time
Stress-Waves

- "static" stress component is due to thermal gradients
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- "dynamic" stress component is due to stress waves
  - Spill time dependent

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- \( T_{\text{spill}} > \text{Radial period} \)
  - Radial stress waves are not significant

**Effect of Spill Duration on Peak Dynamic Stress in the Target**
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*Effect of beam spill time on the peak dynamic stress in the 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

- **Tspill > Radial period**
  - Radial stress waves are not significant

- **Tspill < Longitudinal period**
  - Longitudinal stress waves are important!

![Graph showing effect of spill duration on peak dynamic stress in the target Free Beryllium Cylinder (Ø21mm L1000mm, beam-sigma = 3.5mm)](image)

Effect of beam spill time on the peak dynamic stress in the target
Conclusions on combined target/horn IC

• Very simple design concept
• But complex, combined horn current pulse and beam pulse effects
• Need to reduce longitudinal Lorentz stresses requires target diameter to be larger than desired for optimum pion yield
• Effects of off-centre beam ‘violin modes’ problematic, in combination with longitudinal vibration modes
• Recommend looking at longitudinally segmented target separate from horn
Direct water cooling?
Effects of pulsed beams on NuMI target

Beam induced temperature jump at the downstream end of the target (z = 94 cm)

Simulation:

Result:

ΔT

Conclusions:
Try to avoid using contained water in close proximity to intense pulsed beams
Pressurised helium cooled concept (2 MW)
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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>

Otto Caretta & Tristan Davenne
LBNE target study: conclusions for 2.3 MW

- Combined target/horn inner conductor
  - Not recommended as dimensions dominated by horn current pulse Lorentz forces rather than pion production

- Candidate beryllium target technologies for further study:
  1. Water cooled longitudinally segmented (possible)
  2. Pressurised helium cooled separate spheres (recommended)
EURONu Super Beam study using HP SPL -> Frejus

50 Hz horn operation and 4 MW beam power on target ‘very challenging’
⇒ 4 x 12.5 Hz operation using beam separator proposed

Beam parameters used:
• Beam KE: 4.5GeV
• 1.11e14 protons/bunch
• Beam Sigma: 4mm
• Beam Power: 4 x 1 MW
Stress in a solid peripherally cooled beryllium rod

1 MW beam power = limit for a solid peripherally cooled target for this beam energy

Peter Loveridge
“Pencil” Target Concept Design

- Pencil shaped Beryllium target contained within a Titanium “can”
- Pressurised Helium gas cooling, outlet at 10 bar
- Supported as a cantilever from the upstream end

Drawing not to scale!
Optimisation of channel profile: it works...

**Cooling channel**

R1 = 9mm  
R2 = 9mm  
R3 = 14.4mm

Mass flow rate 0.06 [ kg s\(^{-1}\) ]  
Pressure Drop = 127338 [ Pa ]  
Helium max velocity 283.676 [ m s\(^{-1}\) ]  
Helium delta T = 73.3873 [ K ]

Helium velocity maximum at shower maximum

Mike Fitton
But: ‘dancing on head of pin’ for off-centre beam

- Lateral deflection 50% greater, and in opposite direction, to beam mis-steer

Energy deposition for 2 sigma beam offset

0 mm

=> Unstable

13 mm

=> not recommended
How about that particle bed idea?

Helium gas cooled granular target proposed by Sievers and Pugnat
Pion production comparison (FLUKA)

ρ(Ti) = 4.506 g/cm³
0.74 ρ(Ti) = 3.336 g/cm³
ρ(graphite) = 1.85 g/cm³

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>downstr. face</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.11 π⁺/p</td>
</tr>
<tr>
<td>Ti</td>
<td>1.29 π⁺/p</td>
</tr>
<tr>
<td>Ti P.B.</td>
<td>1.20 π⁺/p</td>
</tr>
</tbody>
</table>

PB := pebble-bed 74 % ρ

L = 78 cm
R = 1.5 cm

Z coordinate of pions taken at target exit

Longitudinal profile with PB “similar” to the graphite one (and more π!)

→ The horn should work well

A. Longhin

Third EUROnu annual meeting, RAL 18 Jan 2011
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
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
Packed Bed Model (FLUKA + CFX v13)

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

T. Davenne
Packed Bed temperatures

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

Outer Can Surface Temp
Almost Symmetric Temperature contours
Maximum surface Temperature = 426K = 153°C

NB windows not included in model yet
- Double skin Be should withstand both heat and pressure loads
And finally: a flowing powder target for the highest beam powers?

Test rig at RAL

Still image from video clip of tungsten power ejected from 1.2 m long x 2 cm diameter pipe

On-line 'Powder thimble' experiment on HiRadMat planned for this autumn
Conclusions: ‘Divide and Rule’ for higher powers

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

Static, low-Z target concepts proposed for 4 x 1 MW for SPL SB @CERN and 2 MW for LBNE @FNAL