Megawatt target studies for Neutrino Super-Beams

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Contents

- LBNE 2.3 MW Super Beam design study results
- SPL Super Beam design study for EUROnu
- General principles mixed in throughout
Beam and target pulsed and total powers

- **Mu2e (8GeV, 25kW, 588kHz, 100ns, 1mm)**
- **T2K (30GeV, 750kW, 0.47Hz, 5μs, 4.24mm)**
- **Numi (120GeV, 400kW, 0.53Hz, 8μs, 1mm)**
- **Nova (120GeV, 700kW, 0.75Hz, 8μs, 1.3mm)**
- **LBNE (120GeV, 2.3MW, 0.75Hz, 10μs, 1.5mm+)**
- **ISIS (800MeV, 160kW, 50Hz, 200ns, 16.5mm)**
- **EURONu (4.5GeV, 4MW, 50Hz, 5μs, 4mm)**
- **Neutrino Factory (8GeV, 4MW, 50Hz, 2ns, 1.2mm)**
- **ESS (2.5GeV, 5MW, 14Hz, 2.86ms)**
- **ADSR**
T2K Target and horn designed for 750 kW
Effect of Spill Duration on Peak Dynamic Stress in the T2K Target
Cantilevered Graphite Cylinder (Ø26mm L900mm, beam-sigma = 4.24mm)
0.75MW beam power (3.3e14 protons/spill @ 30 GeV, 0.4735Hz rep-rate)
Material Properties @ 400°C

- Radial Oscillation Period: 16 µsec
- Longitudinal Oscillation Period: 1.4 msec

Static Stress Component = 2.4 MPa
Dynamic Stress Component For 4.2 µsec spill = 5.4 MPa

Stress wave magnitude determined by $t_{spill} < t_{radial period}$
LBNE study: Combined target and horn inner conductor (a la K2K)
LBNE study: Stress-Waves in Be rod

- "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!

Effect of beam spill time on the peak dynamic stress in the target
Effects of accidental $2\sigma$ off-centre beam on 'violin mode' stress waves in simply supported target rod.

![Graph showing peak stress with off centre beam](image)

- Peak Von-mises stress as a result of $2\sigma$ off centre beam [MPa]
- Diameter of cylinder or sphere [mm]

- 0.7 MW spheres
- 2.3 Mw spheres
- 0.7 MW cylinder
- 2.3 MW cylinder

- Nominal yield strength and endurance limit for beryllium
- Max design stress (as specified by Fermilab)
Lorentz forces on horn inner conductor

Longitudinal force in inner conductor

\[ F_{\text{long}} = \frac{\mu_0 I^2}{4\pi} \ln\left(\frac{R_2}{R_1}\right) \]

As target/inner conductor size decreases:

- Longitudinal force increases
- Cross sectional area decreases
- ‘Double whammy’ effect on stress
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
LBNE 2.3 MW study: Pressurised helium cooled concept
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Heat transfer coefficient

mid-plane temperatures

Otto Caretta & Tristan Davenne
**LBNE 2.3 MW study:**
*Pressurised helium cooled concept*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Beryllium sphere diameter</td>
<td>13 mm</td>
</tr>
<tr>
<td>Beam sigma</td>
<td>2.2 mm</td>
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<tr>
<td>Helium mass flow rate</td>
<td>17 g/s</td>
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<tr>
<td>Inlet helium pressure</td>
<td>11.1 bar</td>
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<tr>
<td>Outlet helium pressure</td>
<td>10 bar</td>
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<tr>
<td>Inlet velocity</td>
<td>40 m/s</td>
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<td>Maximum velocity</td>
<td>185 m/s</td>
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<tr>
<td>Total heat load</td>
<td>9.4 kW</td>
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<tr>
<td>Maximum beryllium temperature</td>
<td>178 C</td>
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<tr>
<td>Helium temperature rise, $\Delta T$ ($T_{in} - T_{out}$)</td>
<td>106 C</td>
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</table>
EURONu Super Beam study using HP SPL -> Frejus

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

Beam parameters used:
• Beam KE: 4.5GeV
• 1.11e14 protons/bunch
• Beam Sigma: 4mm
• Beam Power: 4 x 1 MW
Why consider a packed bed target?

- Small target segments result in low thermal stress and also low inertial stress (stress waves and excited natural frequencies)
- Not sensitive to off centre beam
- Structural integrity not dependant on target material
- High surface to volume ratio throughout target enables significant heat removal while maintaining reasonable target temperature, (particularly suited to ‘low’ energy beam and high energy density)

Points to note

- Lends itself to gas cooling
- High power designs require pressurised gas
- Bulk density lower than material density (approx factor of 2) may result in a reduction in yield compared to a solid target made of the same material.
- Suitable alternative materials with higher density may be preferred
- Outstanding question over wear due to relative motion of segments with a pulsed beam

Some relevant papers:

- A helium gas cooled stationary granular target (Pugnat & Sievers) 2002
- Conceptual Designs for a Spallation Neutron Target Constructed of a Helium-Cooled, Packed Bed of Tungsten Particles (Ammerman et al.)
- The “Sphere Dump” – A new low-cost high-power beam dump concept (Walz & Lucas) 1969
Where does a Packed Bed Target fit?

- **Beam Power**
  - Solid Peripherally cooled Target (Simple, well proven)
  - Packed Bed or segmented Target (A bit more complex, less experience)
  - Flowing Target - powder jet, mercury jet (Much harder, very complex)

- **Limiting factors**
  - Heat Transfer Area
  - Thermal and Inertial Stress
  - Off axis beam
  - Helium Pressure
  - Radiation damage
  - Window components
  - Reliability
  - Complexity
  - Development Time
Simple packed bed target model

Assume parabolic energy deposition profile

\[ Q = 4P \left( \frac{y}{W} - \frac{y^2}{W^2} \right) \]

Obtain gas temperature as a function of transverse position

\[ T_g(y) = \int_0^y \frac{S Q}{mC_p} \, dy = \frac{4SP}{mC_p} \left( \frac{y^2}{2W} - \frac{y^3}{3W^2} \right) \]
Energy Deposition calculated from FLUKA for 1 MW 4.5 GeV beam

FLUKA compound model used to determine energy deposited in target material

Temperature profile a function of energy deposition, $Q$, radius and thermal conductivity, $k$

$$T_c = T_s + \frac{2Q(y)R^2}{6k}$$
Sphere Temperature for 3mm Ti6Al4V spheres

Sphere core temperature is seen to depend on gas temperature and energy deposition, variation in thermal conductivity with temperature is also accounted for.

Empirical Nusselt number correlation for heat transfer in packed bed (Achenbach et al.)

\[ Nu = \frac{h_d}{k_g} = \left[ (1.1 \text{Re}^{0.58})^4 + (0.23 \text{Re}^{0.75})^4 \right]^{0.25} \]
Sphere Stress: Steady state thermal component

\[
\sigma_{VM\max} = \frac{2EaQR^2}{15k(1-v)}
\]

Low temperature gradient
\(\Rightarrow\) Low stress

NB Long pulse (600 \(\mu\)s)
+ Small particle size
\(\Rightarrow\) low inertial stress
Results Summary for EUROnu
24mm wide cannister packed with 3mm diameter Ti6Al4V spheres.

1.3MW looks reasonable
4MW more challenging but does not look impossible

<table>
<thead>
<tr>
<th>Beam Energy</th>
<th>Beam Sigma</th>
<th>Beam Power</th>
<th>Maximum Power Deposition</th>
<th>Target Width</th>
<th>Sphere diameter</th>
<th>Sphere Material</th>
<th>Helium Pressure</th>
<th>Flow rate per unit surface</th>
<th>Maximum Helium Temperature</th>
<th>Sphere Core Temperature</th>
<th>Max Sphere VM stress</th>
<th>yield stress/ max VM stress</th>
<th>Pressure Drop</th>
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<tr>
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<td>4mm</td>
<td>1MW</td>
<td>2.2e9W/m3</td>
<td>24mm</td>
<td>3mm</td>
<td>Ti6Al4V</td>
<td>10bar</td>
<td>50 kg/s per m²</td>
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<td>49MPa</td>
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<td>3mm</td>
<td>Ti6Al4V</td>
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<td>66 kg/s per m²</td>
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<td>65MPa</td>
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<td>Ti6Al4V</td>
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<td>133 kg/s per m²</td>
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<td>116MPa</td>
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</table>
How to achieve symmetrical transverse flow?

Packed Bed Target Concept

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

Model Parameters
Proton Beam Energy = 4.5 GeV
Beam Power = 1 MW
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
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 (dependent 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

Velocity vectors showing inlet and outlet channels and entry and exit from packed bed
Helium Flow

**Helium Velocity**
Maximum flow velocity = 202m/s
Maximum Mach Number < 0.2

**Helium Gas Temperature**
Total helium mass flow = 93 grams/s
Maximum Helium temperature = 857K = 584°C
Helium average outlet Temperature = 109°C
Titanium spheres

High Temperature region
Highest temperature Spheres occur near outlet holes due to the gas leaving the cannister being at its hottest

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

Pressure contours on a section midway through target
Helium outlet pressure = 10bar
Helium inlet pressure = 11.2bar
Majority of pressure drop across holes and not across packed bed
Target Beam Window

- Beam enters the target cannister through a beam window which separates target coolant from target station helium.

- Beryllium is a candidate material for the window.

- Peripheral or surface cooling look to be feasible options.

- Static and inertial stresses result from beam heating are manageable.

- Pressure stresses can be dealt with by having a hemispherical window design.
Packed Bed Testing

Induction Heating
Packed bed placed in an alternating magnetic field.
Eddy currents induced in conductive spheres.
Resultant Joule heating provides internal heating of spheres.

Duquenne et al.

\[
R_{\text{eq packed bed}} = 4(1 - \varepsilon) \left( \frac{\pi^2 R^2 N^2}{\tau_s L} \right) \left( \sqrt{10^{-7} \mu_R f / \sigma} \right) F
\]

Figure 3 — (a) Path of the eddy currents at the surface of a sphere; (b): sectional view of eddy currents in a well-ordered pile of spheres; (c): sectional view of eddy currents in a cylinder; (d): analogy between a randomly-packed bed; (e): regular piles of particles; (f): a bundle of cylinders.

Packed bed induction heating theory
Graydon et al.
Conclusions for SPL Super Beam target

- A packed bed target has been adopted as the baseline target design for the EUROnu superbeam. It offers:
  - Inherently low steady state and inertial stress as well as tolerance to off-centre beams.
  - A potential design up to 4MW beam power while the more conventional solid target is limited to less than 1MW beam power.

- A CFD model of a packed bed target concept for 1MW beam power indicates the feasibility of such a target.

- Stress in window components, containment vessel, required operating pressure and radiation damage may be the limiting factors for a packed bed target, however heat dissipation is less of a problem.

- Vibration levels and relative motion and wear between spheres is as yet an unknown and so an in-beam test would be useful.

- Induction heating offers potential for an offline test of the heat transfer and pressure drop characteristics of a packed bed design.
General conclusions: ‘Divide and Rule’ for greater power

Dividing material generally favoured since:
• Better heat transfer
• Lower static thermal stresses
• Lower dynamic stresses from intense beam pulses (NB benefit depends on target dimensions/beam pulse length)

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
Viet Nus 2012
‘Beam Challenges’ working group topics

• Are there any modifications to existing beams which can be carried out to aid in the delivery of useful information?
• Is there a way to reduce NC background?
• Are there particular neutrino energies which are easier to deliver?
• Is there an advantage to a lower energy WBB?
• Registration is open!
The 8th Rencontres du Vietnam

Viet Nus 2012 Workshop

Toward CP Violation In Neutrino Oscillations

Qui Nhon, Vietnam Dec 17-22, 2012
Packed Bed Target for a neutrino factory?

- A titanium packed bed offers a potential design to dissipate the heat load from a 4MW 4.5GeV proton beam.
- The neutrino factory baseline beam pulse has a challenging 2ns pulse length.
- Some evidence to suggest a low density neutrino factory target would offer comparable physics performance.

![Graph showing average π/μ yield per proton per GeV for different elements and beam energies.](image)
Temperature and stress in a uniformly heated sphere

Temperature profile inside a sphere with uniform heat deposition

1D problem (uniform energy deposition and surface temperature)
r = radial position [m]
T_i = core temperature [K]
T_o = surface temperature [K]
Q = heat load per unit volume (W/m^3)
q(r) = heat flux as a function of r [W/m]
R = radius of sphere [m]
k = thermal conductivity of sphere [W/m/K]

\[ q(r) = \frac{Q}{2\pi r^3} \]
\[ q(r) = -kA \frac{dT}{dr} = -4\pi r^2 k \frac{dT}{dr} \]
\[ T = \int \frac{q(r)}{4\pi r^2 k} dr - \frac{T_i}{4\pi k} + C \]

Applying boundary conditions T=T_o at r=R and T=T_o at r=0 gives
\[ T = T_o + \frac{Q}{4\pi k} (R^2 - r^2) \] temperature as a function of r

\[ \Delta T = T_r - T_o = \frac{Q}{4\pi k} \]

Example for titanium alloy:

k = 7.2 W/m/K
R = 1.5 mm
Q = 3.1e9 W/m^3
\[ \Delta T = 161.5 K \]

Stress distribution inside a sphere with uniform heat deposition

In general form, the radial and azimuthal thermal-stress components inside a sphere where the temperature varies as a function of radius are given by:

\[ \sigma_r = \frac{2E\alpha}{(1-\nu)} \left( 1 - \frac{1}{2} \frac{Tr^3 dr}{R^3} \right) \]
\[ \sigma_\theta = -E\alpha \left( 1 - \frac{1}{2} \frac{Tr^3 dr}{R^3} + \frac{2}{R^3} \frac{Tr^3 dr - T}{R^3} \right) \]

Where E is elastic modulus, \(\alpha\) is linear expansion coefficient, and \(\nu\) is poisson ratio. In Tristan's case (above) recall that the temperature distribution was:

\[ T = T_i + \frac{Q(R^2 - r^2)}{6k} \]

Substituting and performing the integration yields the radial and azimuthal thermal-stress components as a function of radius for this particular case:

\[ \sigma_r = \frac{E\alpha Q(r^2 - R^2)}{15k(1-\nu)} \]
\[ \sigma_\theta = \frac{E\alpha Q(2r^3 - R^3)}{15k(1-\nu)} \]

The Equivalent Von-Mises Stress comes from:

\[ 2\sigma_{VM}^2 = (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \]

In this case leading to:

\[ \sigma_{VM} = |\sigma_1 - \sigma_2| \]

The Von-Mises stress as a function of radius is then:

\[ \sigma_{VM} = \frac{E\alpha Qr^3}{15k(1-\nu)} \]

It is at a maximum at the outer radius where \( r = R \). So:

\[ \sigma_{VM,\text{max}} = \frac{E\alpha QR^3}{15k(1-\nu)} \]

Taking \( E = 114 \) GPa, \( \alpha = 8.7e-6 /^{\circ}\)C, \( \nu = 0.34 \), gives \( \sigma_{VM,\text{max}} = 97 \) MPa

Temperature Distribution in a 3mm diameter Titanium Sphere

Stress Distribution in a 3mm diameter Titanium Sphere
Packed Bed Notes

The Ergun equation, relates the friction factor in a packed column as a function to the Reynolds number:

\[ f_p = \frac{150}{Gr_p} + 1.7555 \]

where \( f_p \) and \( Gr_p \) are defined as

\[ f_p = \frac{\Delta p}{L} \frac{D_p}{\rho V_s^2} \left( \frac{\varepsilon^3}{1 - \varepsilon} \right) \]
\[ Gr_p = \frac{D_p V_s \rho}{(1 - \varepsilon) \mu} \]

where: \( \Delta p \) is the pressure drop across the bed,
\( L \) is the length of the bed (not the column),
\( D_p \) is the equivalent spherical diameter of the packing,
\( \rho \) is the density of fluid,
\( \mu \) is the dynamic viscosity of the fluid,
\( V_s \) is the superficial velocity (i.e. the velocity that the fluid would have through the empty tube at the same volumetric flow rate), and
\( \varepsilon \) is the void fraction of the bed (Bed porosity at any time).

CFX v13 uses two Energy Equations, one for fluid and one for solid with interfacial heat transfer applied as an equivalent source/sink term in each equation.
Overall heat transfer coefficient and interfacial area defined to account for thermal conductivity through solid components of packed bed as well as forced convection between gas and solid.