EUROnu Beam Window Studies

Stress and Cooling Analysis

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T2K beam window

- Double-skinned titanium alloy window, cooled by helium gas.
- LBNE plan to use a similar design for their beam window. But perhaps beryllium instead of titanium.
- Cost ~ $100k
T2K Target Station

Proton beam

Window

Target

Focusing horns

Concrete shield (1m)

Iron shield (2.2m)
Double skinned window with helium cooling
Main components

Top plate
- Used for inserting and removing window
- Protects pillow seals and mating flanges
- Provides a connection point for services

Pillow seals
- Seal helium vessel and beam line (leak rate spec, $1 \times 10^{-7}$ Pam$^3$/s)

Side plates
- Provide a firm support for the beam window to hold it in position

Ti-6Al-4V beam window
Inflatable seals

Picture courtesy of Y. Miyake and S. Makimura (KEK)

Picture courtesy of PSI

Picture courtesy of PSI

PSI

KEK Muon Group
Seal and mating flange

- Seal foils (surface roughness, \(Ra = 0.004 \, \mu m\), \(Rt = 0.030 \, \mu m\))
  - Polished flange (surface roughness, \(Ra = 0.020 \, \mu m\))

  Leak performance \(\sim 1 \times 10^{-9} \, Pa.m^3/s\)

  Cost: \(\sim $30,000\) each
# EUROnu window candidate materials

<table>
<thead>
<tr>
<th></th>
<th>Beryllium</th>
<th>Titanium alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1844</td>
<td>4540 kg/m³</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1925</td>
<td>558 J/kg.K</td>
</tr>
<tr>
<td>CTE</td>
<td>11.5</td>
<td>8.7</td>
</tr>
<tr>
<td>Modulus</td>
<td>303</td>
<td>113 GPa</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>216</td>
<td>7 W/m.K</td>
</tr>
</tbody>
</table>

Others candidates: AlBeMet, GUM, INVAR…
Simple stress comparison

‘Thermal stress resistance’,

\[ R = \frac{UTS}{\alpha \cdot E \cdot \Delta T} \]

where

\[ \Delta T = \frac{EDD}{C_p} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( \Delta T )</th>
<th>Shock resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>100</td>
<td>10.05</td>
</tr>
<tr>
<td>beryllium</td>
<td>37</td>
<td>2.08</td>
</tr>
<tr>
<td>titanium</td>
<td>245</td>
<td>4.12</td>
</tr>
<tr>
<td>albemet</td>
<td>51</td>
<td>3.26</td>
</tr>
</tbody>
</table>

UTS – ultimate tensile strength
\( \alpha \) – coefficient of thermal expansion
E – Young’s modulus
\( \Delta T \) – temperature jump
EDD – energy deposition density
\( C_p \) – specific heat capacity
## Superbeam comparison

<table>
<thead>
<tr>
<th></th>
<th>EUROnu (700 kW)</th>
<th>LBNE (2 MW)</th>
<th>T2K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam power</strong></td>
<td>1</td>
<td>0.7</td>
<td>2</td>
</tr>
<tr>
<td><strong>Beam energy</strong></td>
<td>5</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td><strong>Protons per pulse</strong></td>
<td>1.50e14</td>
<td>5.60e13</td>
<td>1.6e14</td>
</tr>
<tr>
<td><strong>Beam sigma</strong></td>
<td>4</td>
<td>1.5</td>
<td>3.5</td>
</tr>
<tr>
<td><strong>Peak energy dep.</strong></td>
<td>~ 80</td>
<td>~ 200</td>
<td>~ 128</td>
</tr>
<tr>
<td><strong>Pulse length</strong></td>
<td>5</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>12</td>
<td>1.32</td>
<td>1.32</td>
</tr>
</tbody>
</table>

**NOTE:** Energy deposition is for beryllium.
Euronu stress analysis – variables studied

**Beam parameters:**
- Power: 1 MW (4 MW divided between four targets/windows)
- Energy: 5 GeV
- $1.5 \times 10^{14}$ protons per pulse
- Frequency: 12.5 Hz
- Pulse length: 5 microseconds
- Beam sigma: 4 mm

**Design considerations:**
- Materials: Beryllium (S65C), Titanium alloy (Ti-6Al-4V)
- Cooling methods: direct forced convection helium and circumferential water

Beam parameters taken from *EUROnu WP2 Note 09-11*
Typical ANSYS model showing cooling options

ANSYS Multiphysics v11 used with coupled field elements (axisymmetric model)
Energy deposition profile

NOTE: Data produced by Tristan Davenne (RAL) using Fluka. A Gaussian approximation of this data has been used in ANSYS for simplicity. Peak is around 80 J/cc/spill for beryllium window.
Transient animation

NODAL SOLUTION
TIME=.200E-03
/EXPANDED
TEMP (AVG)
RXY=0
SN=50
SMX=32.459

MARCH 12 2010
11:03:21

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Matt Rooney, March 2010
Helium cooled Ti-6Al-4V window (like T2K) is not an option

0.25 mm thick titanium alloy window
Direct helium cooling (assumes 1000 W/m²K)

Peak stress of 500 MPa is above yield stress for titanium at 800°C.
Circumferentially water cooled beryllium window

0.25 mm thick beryllium window
Circumferentially water cooled
(assumes 2000 W/m²K)
Max temp ~ 180 °C
Max stress ~ 50 MPa (yield ~ 270 MPa)
Acceptable!
High velocity helium cooled beryllium window

0.25 mm thick beryllium window
Direct helium cooling  
(assumes 1000 W/m²K)
Max temp 109 °C
Max stress 39 Mpa
Better!
Shock animation
‘Shock’ stress due to single pulse in beryllium window

Temp jump of 22°C results in 50 MPa peak stress. When superimposed with other stresses the peak may be around 70 MPa, giving a SF of around 4 on the UTS.
Yield strength of beryllium @ 260°C is around 200 MPa. This leaves a safety factor of about 2 for a beryllium neutrino factory window with these beam parameters.
Conclusions

1. High frequency beam makes cooling the main challenge for any window. Actual thermal stress due to each pulse is within acceptable limits.

2. Difficulty in cooling a titanium window makes this a bad choice for EUROnu beam parameters.

3. High frequency beam with low protons per pulse makes beryllium window a possibility due to its high thermal conductivity. Either direct helium cooling on the beam spot or circumferential water cooling may be feasible.

4. Neutrino factory window may be possible with this beam parameters, though safety factor is small and radiation damage would quickly become an issue.