The JPARC neutrino target

KEK
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(For J-PARC target/monitor Group)

High-power targetry for future accelerators
Ronkonkoma, NY.
Next generation LBL experiments in Japan
“J-PARC - Kamioka neutrino project”

Baseline ~295km
Conventional $\nu_\mu$ beam

Beam Energy ~1GeV
Will be adjusted to
the oscillation maximum

Beam power
Far detector
Physics

0.75MW
Super Kamiokande (50kt)
disappearance $\nu_\mu \rightarrow \nu_X$
appearance $\nu_\mu \rightarrow \nu_e$
NC measurements
J-PARC facility

JAERI@Tokai-mura (60km N.E. of KEK)

Construction
2001～2006 JFY
(Approved in Dec.2000)

<table>
<thead>
<tr>
<th></th>
<th>J-PARC</th>
<th>K2K</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GeV)</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>Int. ($10^{12}$ppp)</td>
<td>330</td>
<td>6</td>
</tr>
<tr>
<td>Rate (Hz)</td>
<td>0.275</td>
<td>0.45</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>750</td>
<td>5.2</td>
</tr>
</tbody>
</table>
JPARC neutrino beamline

Proton beam kinetic energy
50GeV  (40GeV@T=0)

# of protons / pulse
3.3\times 10^{14}

Beam power
750kW

Bunch structure
8 bunches

Bunch length (full width)
58ns

Bunch spacing
598ns

Spill width
\sim 5\mu s

Cycle
3.53sec
Off Axis Beam (another NBB option)
(ref.: BNL-E889 Proposal)

WBB w/ intentionally misaligned beam line from det. axis

Far Det.

 Decay Kinematics

$$\pi (m_\pi p_\pi) \rightarrow \nu (E_\nu) \rightarrow \mu (m_\mu p_\mu)$$

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos \theta)}$$

Quasi Monochromatic Beam
Target station

22m

11m

33m

40ton crane

Ground level

Service pit

Machine room

He container

Cooling

Waste storage area

Concrete

Beam window

Iron shield

Baffle

Target+1st horn 2nd horn 3rd horn

100 cm
Target for JHF neutrino

Requirements

Solid target       Easy to handle
melting point should be high enough.

Thermal shock resistance

Candidate

→ Graphite Target

Melting point       ~ 3550°C
Thermal conductivity ~ 100W/m·K
Thermal expansion    ~ 4 × 10^{-6} / °C
Young’s modulus      ~ 10GPa
Determination of the size (radius) of the target

External conditions

• **Inner radius of the horn**
  - minimum: \( r_{\text{target}} \approx 10\text{mm} \)
    (heat load from radiation)
  - maximum: \( r_{\text{target}} \approx 15\text{mm} \)
    (pions are not well focused)

(Target needs to be embed in the 1st horn to focus pions efficiently.)

• **Size of the beam at the target**
  - Larger than \( \sigma_r \approx 0.4\text{cm} \)
    (for \( 24\pi \) mm mrad beam)

Radius of the target: \( 10 \sim 15\text{mm} \)
Determination of the size (radius) of the target

Yield of pions (=neutrinos)
Smaller is better (reduce the absorption of pions)

But even if we change diameter from 20mm to 30mm,
the difference of # of π is ~5%

effect of the π absorption in this region is fairly small
Energy deposit in the target

Target and beam size dependence

**Carbon (density 1.81 g/cm³)**

\[ \phi = 2\text{cm}, \sigma_{\text{beam}} = 0.4\text{cm} \]

\[ \phi = 3\text{cm}, \sigma_{\text{beam}} = 0.6\text{cm} \]

This time, we used the target with \( \phi=30\text{mm} \) in the calculations and the simulations.
Estimation the temperature rise

Material properties used in the simulation

Temperature dependences have to be taken into account.

Specific heat

- Increased at higher temp.
- Temperature rise is overestimated

Maximum temperature rise ($\Delta T_{\text{max}}$)

- Constant ~240K
- Temp. dependent ~170K

Thermal conductivity

- Decreased at higher temp.
- Temperature at the center of the target is underestimated
  (Still, far below the melting point)
Estimation of the temperature rise

Parameters

- Thermal convection coefficient = 6.5 W/m²/K
- Temperature of the surrounding area = 30°C (fixed)

just after the spill
(after 5 µs)

- ~ 225°C @ r = 0, z ~ 160 mm
- ~ 77°C @ r = 15, z ~ 700 mm

just before the next spill
(after 3.53 s)

- ~ 55°C @ r = 0, z ~ 510 mm
- ~ 46°C @ r = 15, z ~ 510 mm

M. Minakawa, Y. H.
Time dependence of temperature

Maximum temperature

Center (r=0mm) 
\[ \sim 225^\circ C \]
far below the melting point

Surf ace (r=15mm) 
\[ \sim 75^\circ C \]
(temperature of the surrounding area was fixed at 30 °C)

Consider direct water cooling

To keep the surface temperature below 100°C,
water temperature should not exceed \( \sim 50^\circ C \).
Thermal convection coeff. needs to be larger than \( \sim 6kW/m^2/K \).

Is it possible?
Cooling test

According to the results from the calculations, the heat transfer rate is larger than \(~6\text{kW/m}^2/\text{k}\).

Heat up the target with DC current and try to cool by the flowing water.

Measure water flow rate and temperature at various points to estimate the heat transfer rate.
Cooling test set up

Heat transfer rate measurement

Thickness of the water path: 2mm
Radius of the target: 15mm
Water temp. (in) ~25°C
DC Current: up to 1.3kA

corresponds to ~ 20kW
Cooling test results

Results & calculations

Theoretical formula

\[ \alpha = 0.023 \times \text{Re}^{0.8} \times \text{Pr}^{0.4} \times \lambda \times d^{-1} \]

- \( \text{Re} \) Reynolds number
- \( \text{Pr} \) Prandtl number
- \( \lambda \) Thermal conductivity
- \( d \) equivalent diameter

\( \text{(Re and Pr also depend on the surface temp.)} \)

Measurements and theoretical calculations seem to agree

\[ \alpha > 6\text{KW/m}^2/\text{k} \quad \text{can be achieved when} \]

the flow rate is more than 18 l/min.
Change of the material properties by neutron irradiation

The thermal conductivity is largely reduced by the neutron irradiation effect (about by factor 10.)

T. Maruyama et al., J. of nucl. materials, 195(1992), 44-50

Reduce the thermal conductivity by factor 10 in the simulation.

Temperature at the center was increased but it was saturated after 10 spills and the maximum temperature was less than 400°C. (Temperature of the surface did not change or slightly reduced.)

Effect of the neutron irradiation on thermal conductivity will not be the problem.
Actual design of the target

Direct cooling or put in the container?
This time, we tested the “direct cooling”.
It seems to be working.

But
• The target will not be dissolved?
• If water get into the deep inside of the target ...
  Boiled when the beam hits the target (?)
• 90cm long target can not be made by using the best material.

If we put the target in a metal container,
water does not contact with the target,
it is possible to cut the target in small pieces,
even if the target brakes up,
the target material does not flow away.

We are planning to put the target in a container
and measure the heat transfer rate.
Estimation of the thermal stress

Material properties used in the simulation

- **Thermal expansion coeff.**
  - Plot showing the thermal expansion coefficient for Tokai Carbon G347 as a function of temperature.
  - The coefficient increases with temperature.

- **Young’s modulus**
  - Plot showing the Young’s modulus for Tokai Carbon G347 as a function of temperature.
  - The modulus increases with temperature.

*If these temperature dependences are taken into account, the estimated thermal stress will be increased.*
Estimation of the thermal stress (Analytical)

Analytical calculations

\[
\begin{aligned}
\sigma_z^{\text{stat}} & \approx -\frac{2}{3} \frac{E \alpha T_0}{1 - \nu} \\
\sigma_\phi^{\text{stat}} & \approx -\frac{E \alpha T_0}{3(1 - \nu)} \\
\sigma_r^{\text{stat}} & \approx -\frac{E \alpha T_0}{3(1 - \nu)} \\
\sigma_z^{\text{dyn}} & \approx \pm \frac{1}{3} E \alpha T_0 
\end{aligned}
\]

- $E$: Young's modulus
- $\nu$: Poisson ratio
- $\alpha$: linear expansion coeff. (thermal)
- $T_0$: Temperature

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Equivalent stress (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyo Tanso</td>
<td>IG-43</td>
<td>~7</td>
<td>37.2</td>
</tr>
<tr>
<td></td>
<td>ISO-88</td>
<td>~11</td>
<td>68.6</td>
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<tr>
<td>Poco Graphite</td>
<td>ZXF-5Q</td>
<td>~15</td>
<td>95.0</td>
</tr>
<tr>
<td>Tokai Carbon</td>
<td>G347</td>
<td>~6</td>
<td>31.4</td>
</tr>
</tbody>
</table>

Here, we do not have the data of temperature dependences of the material properties other than G347, we assume that the shape of the temperature dependences are the same.
Thermal stress estimation (ANSYS)

Condition: Simulate the hottest part (z=100mm ~ 200mm)
Both of the edges (z=100 & 200mm) are fixed
just after the spill (after 5µs)

Equivalent stress

@ maximum temperature (r=0,z~170mm) ~8.8MPa.
(analytical calc: 6.0MPa)

[Tensile strength (Tokai Carbon G347) : 31.4MPa]

@ r=0, z=200mm ~14.5MPa.
(Because both of the edges were fixed)

slightly larger but consistent with the analytical calculations (due to the approximation of the temperature distribution)
Water system for the target cooling

We have to remove H₂, N ions and heavy metal ions.
Also, the water have to be cooled. (∆ₜ(water)~15°C@20l/min.)
Radioactive residues

(target and cooling water)

1) Target (By Nakano)
   size \( \phi = 30\text{mm}, \ L = 900\text{mm} \)
   density \( 1.8\text{g/cm}^3 \)
   
   \# of generated Be\(^7\) \(~9 \times 10^{12}(\text{Bq})\)
   after 1yr of running, cooled for 1day \(~14\text{Sv/h}\) 

2) Cooling water (By K.Suzuki)
   after 20 days of running
   Tritium \(~30(\text{MBq})\)
Summary (I)

For the JPARC $\nu$ experiment, solid target R&D is now ongoing.

- **Material**: Graphite (or C/C composite?)
- **Dimensions**:
  - Diameter $\sim 30\text{mm}$
  - Length $900\text{mm}$ (2 interaction length)
- **Cooling**: Water (direct or put in the case?)
  - Heat transfer rate $> \sim 6\text{kW/m}^2/\text{K}$
  - Direct cooling $\rightarrow$ seems to work
    - Water flow rate $\sim 20\text{l/min}$.
- **Temperature rise**: $\sim 175\,^\circ\text{C}$ (center)
  - $\sim 25\,^\circ\text{C}$ (surface)
- **Thermal stress**: $\sim 9\text{MPa}$ (for G347)
  - [Tensile strength (G347) $\sim 31\text{MPa}$]
R&D Items  (We want to test/check the following items.)

• Cooling test
  Set the water flow rate at 20l/min. and confirm the method.
  Measure the heat transfer rates with a target container.

• Stress test
  Beam test (with same energy concentration)  Where?

• Irradiation effects other than the thermal conductivity

• Search for the best material
  (Usually, graphite, whose tensile strength is large,
   has large Young’s modulus.
   → the thermal stress is also getting larger.)

  Temperature dependences of the material properties.
Summary (III)

- Design of the entire system has to be fixed.

How to fix (support) the target, alignments etc...

Machine room

Baffle

Target+1st horn 2nd horn 3rd horn

Concrete

Beam

Window

Concrete

Service pit

Waste storage area

Iron shield

Ground level

40ton crane

Cooling

He container

Waste storage area

Beam window

Target+1st horn 2nd horn 3rd horn
Summary (IV)

• Target handling

How to remove the target from the horn remotely?
(It may be necessary to remove the target from the horn when the target part is broken.)