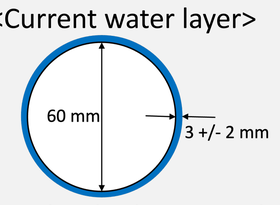
Improved prediction of the T2K neutrino beam flux by estimation of hadronic secondary interactions in the cooling water of magnetic horns using measurement-based material modeling

Sakiko Nishimori, Takeshi Nakadaira[A] , Tetsuro Sekiguchi[A] , Ken Sakashita[A] , Megan Friend[A] , Lukas Berns[B] , Yoshikazu Nagai[C], for T2K Collaboration
(Email : nishimor@post.kek.jp)
SOKENDAI, KEK IPNS[A] , Tohoku Univ.[B] , Eötvös Loránd Univ.[C]

Motivation

- To improve precision of the oscillation analysis, The neutrino flux uncertainty from hadron re-interactions on the cooling water (CW) of magnetic horn needs to be reduced.
- Water layer used in current simulation was determined just by looking at water behavior from a view port. → The accuracy is not guaranteed.
- Horn cooling water behavior is investigated by making a horn-1 mock-up for improving the precision of flux uncertainty.
- An image analysis method is developed to determine the thickness of the cooling water layer with improved precision.

<Current water layer>

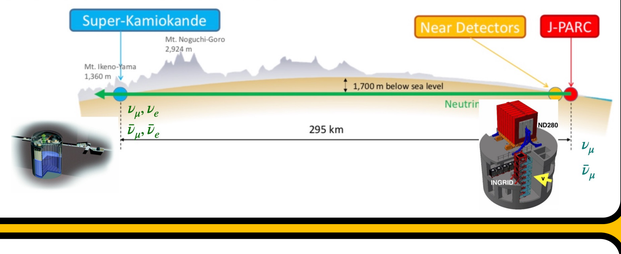


Current estimation is conservative

Improve

1. T2K: Long-baseline neutrino experiment

- Search for CP violation in the lepton sector by precision measurement of neutrino oscillations with accelerator neutrinos.
- Key points to improve precision
  - ➢ increase the beam power
  - ➢ reduce neutrino flux uncertainty

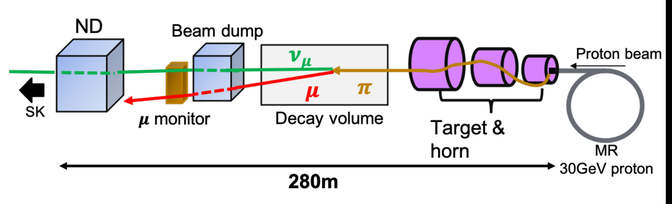


2. Neutrino beamline and the magnetic horn

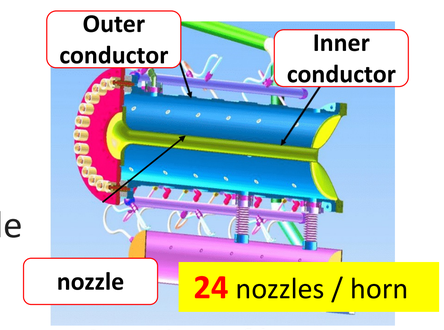
Neutrino production process

Protons collide with C target

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$



- Three magnetic horns to focus secondary pions (horn1-3)
- 320kA pulsed current to create toroidal magnetic field (2.1T max)
- Large heat load (33kJ/pulse@1.3MW) generated by secondary particles and Joule heating
- Water cooling with sprayed water from nozzles (see right picture)



Overview of horn1

3. Effect of horn cooling water to neutrino flux

Precision of neutrino flux estimation

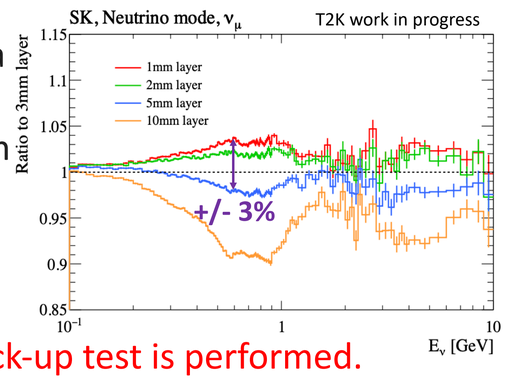
Neutrino flux is estimated using MC simulation.

[Reference]
"T2K neutrino flux prediction"
K.Abe et al, *Phys.Rev.D* 87 (2013) 1, 012001

The secondary interaction of pions with horn CW is the largest effect other than the hadron production.

- The shape of the water is modeled as a uniform layer around the inner conductor with a thickness of 3+/-2mm
- The flux uncertainty due to horn CW is estimated to be about +/-3%. (Total uncertainty: ~ 5 %)

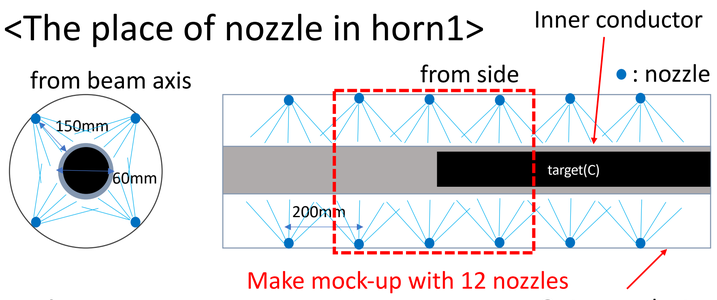
Simulated numu flux

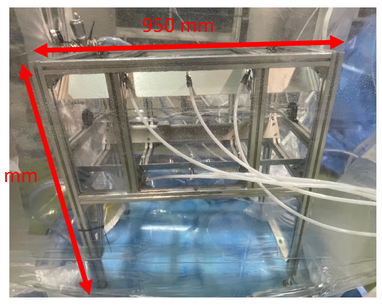


→Improved estimation based on the mock-up test is performed.

4. Mock-up test of horn cooling water

<The place of nozzle in horn1>





<points>

1. Dummy inner conductor (acrylic pipe) and 12 nozzles are located on aluminum structure.
2. Adjustable flow rate (2.5L/min/nozzle) with flowmeters and valves for each nozzle.
3. Directed the beam downward by 3.64 degrees with respect to the horizontal

<Actual Horn>
Flow : 2.5L/min/nozzle
Pressure : 3 atmosphere
(in machine room)

← A video shot from side

5. Developed estimation method of water layer

Definition of the reference line

Reference line (= Pipe outer surface) is defined using the image w/o water spraying.

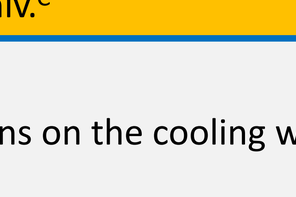
Original

after edge detection

Water edge detection

Canny method :

- Detect and dot points at the pixel where the strong brightness changes.
- the edge → Represented by white pixels



Determination of the thickness

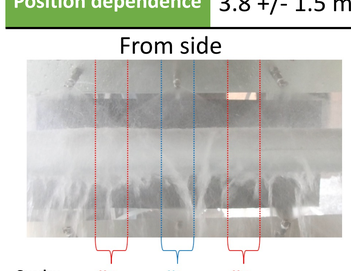
The thickness of the water layer is estimated from the distance between the reference line and edges.
→ Gaussian fit around the peak

Distance between the reference line and edges

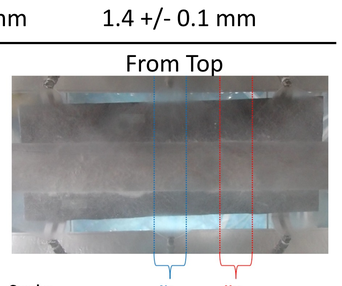
6. Water layer model based on image analysis

	Top	Side
Time dependence	Difference < 0.5 mm	Difference < 0.1 mm
Position dependence	3.8 +/- 1.5 mm	1.4 +/- 0.1 mm

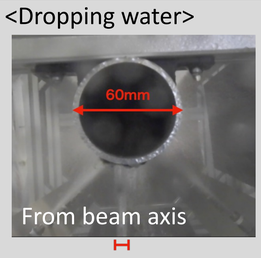
From side



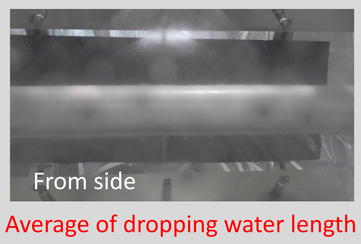
From Top



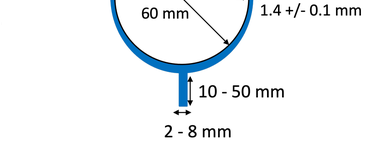
<Dropping water>



Max water width ~8 mm



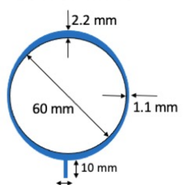
Average of dropping water length seems at least 10 mm.



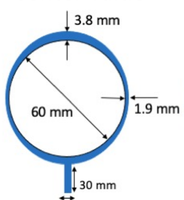
- Position dependence is checked by looking at different parts of the water distribution.
- The top part of the pipe is thicker than the side. This is considered to be because the cooling water on the side falls quickly, whereas the cooling water on the top falls slowly.
- The effects of dropping water width/length: < 0.5 %

7. New water layer in the beam simulation

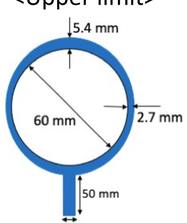
<Lower limit>



<Center value>

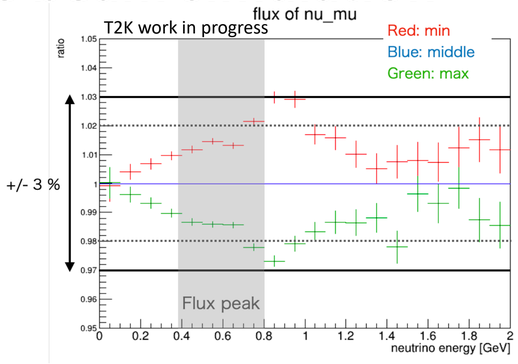


<Upper limit>



[Total flux 0 ~ 2 GeV]
middle -> min: +1.45 %
middle -> max: -1.47 %

[flux 0.4 ~ 0.8 GeV]
middle -> min: **+ 1.48 %**
middle -> max: **- 1.55 %**



8. Conclusion and Future plans

- The flux uncertainty due to CW was improved about twice.

Energy range	Symmetry	New distribution
0 – 2 GeV	+2.4 % / -2.5 %	**+1.5 % / -1.5 %**
0.4 – 0.8 GeV	+2.8 % / -2.8 %	**+1.5 % / -1.6 %**

- The new water distribution will be implemented in the official T2K flux prediction.
- It will improve the precision of neutrino oscillation analysis and CP violation search.

Summary

- New water layer is determined with the mock-up test and beam simulation.
- The flux uncertainty due to the water distribution of the magnetic horn is evaluated to be about twice smaller with the new water layer, which will lead to improve precision of CP violation search.