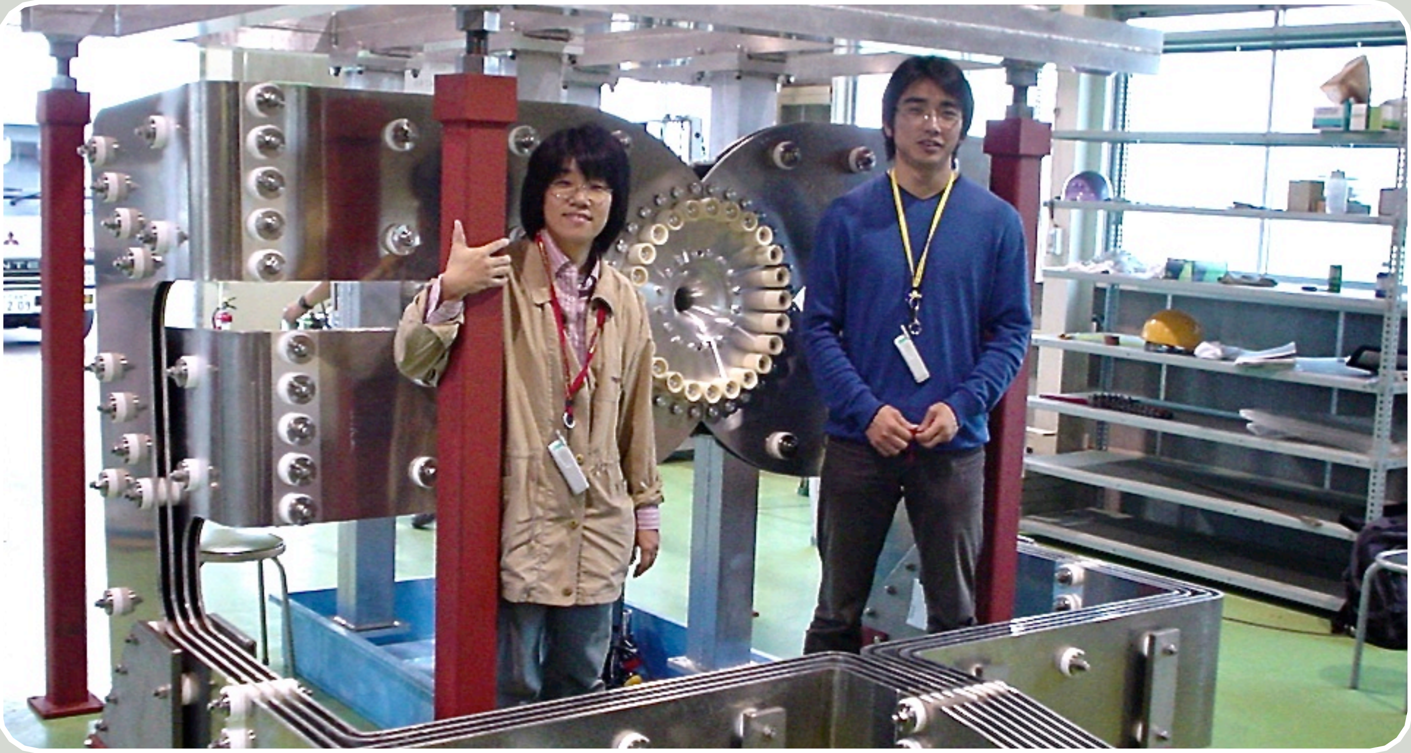
February 16, 2010

FEATURE STORY



Prof. Atsuko Ichikawa (left) of Kyoto University and Dr. Tetsuro Sekiguchi of KEK stand in front of the prototype of the first horn. Ichikawa designed and developed the horns, and Sekiguchi joined the team in 2005 and now leads the horn group.

Beats of neutrino horns

[Neutrino, T2K, Electromagnetic Horn]

Two months into the operation of the Tokai-to-Kamioka neutrino oscillation experiment (T2K), the experiment is now expecting at any moment the first neutrino at the end detector, Super-Kamiokande. This week features the devices at the heart of the T2K experiment, the electromagnetic horns that shape and focus the neutrino beam.

Of the six parameters that determine neutrino oscillation, two have yet to be measured. When Prof. Atsuko Ichikawa (Kyoto University) started her design studies for the next-generation long baseline neutrino oscillation experiment, she thought determining the parameters was so near the reach. Ten years have passed since then. It was a long wait, Ichikawa says, but the goal is now within sight.

T2K sends neutrinos 295 kilometers across Japan, from Tokai to Kamioka. Neutrinos are extremely light particles, and come in three different types: electron, muon, and tau. The different types are known as flavors. During flight, neutrinos can change flavors back and forth. This is called neutrino oscillation.

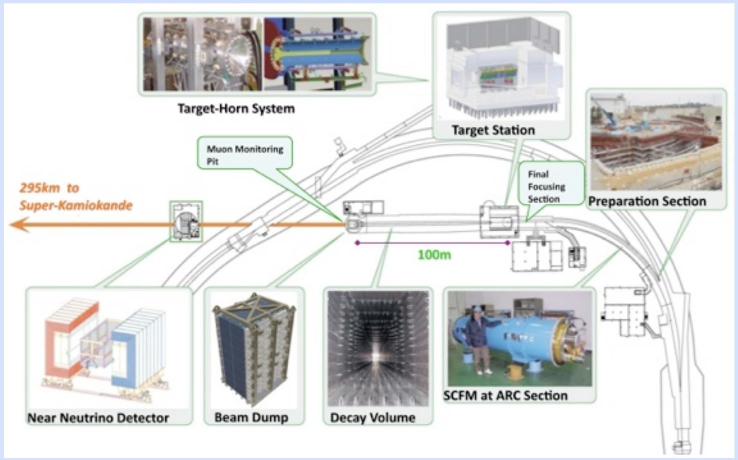
Determining the six parameters which influence the probability of neutrino oscillation is very important to understand the structure and evolution of our universe. These parameters will help physicists understand how ordinary matter (as opposed to antimatter) came to prevail during the early universe.

The T2K experiment uses the 30 GeV proton beam produced at the Japan Proton Accelerator Complex (J-PARC). The high intensity proton beam is extracted from the synchrotron, guided through the neutrino beamline to the T2K target station, where it hits a graphite target, producing pions. These pions quickly decay into muons and muon neutrinos. The detectors at the two ends of the long baseline, the near detector at J-PARC and the far detector Super-Kamiokande at Kamioka, determine the properties of the neutrino beam. Measured properties include energy, momentum, and flavor. Differences in the measurements at the two ends of the experiment are due to neutrino oscillation.

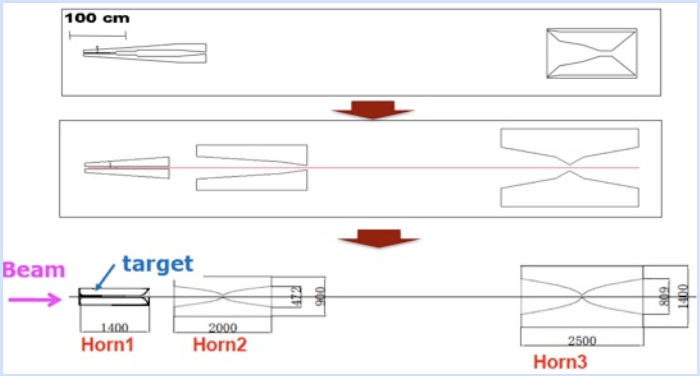
Of the many important components necessary to build such ambitious experiment, the electromagnetic horns, sitting at the very heart of it, are essential. It was in 2000 when Ichikawa became in charge of the component.

The 30 GeV proton beam produces billions of neutrinos. However, because neutrinos interact with ordinary matters only very weakly, most of them pass through the detectors undetected. In fact, Super-Kamiokande is expected to catch only one hundred billionth of them. In order to make the best use of the neutrino beam and catch as many neutrinos as possible, physicists want the neutrino beam focused and aimed as effectively as possible when it departs the J-PARC facility. The problem is that neutrinos are hard to focus precisely because they do not interact with electromagnetic forces. Since focusing the neutrinos is practically impossible, neutrino scientists have chosen a simpler, though indirect, alternative. They use electromagnetic horns to focus the charged pions before they decay into neutrinos in the direction that the pions travel.

The T2K horns have a double-walled aluminum structure, in which 320 kilo-Amperes of current flows from the inner surface back through the outer surface. This creates a strong spiral-shaped magnetic field of 2 Tesla between the aluminum surfaces, bending the paths of charged pions to the forward direction.



When a proton beam hits the graphite target, it produces pions. The pions decay into muons and muon neutrinos. The role of the horns is to focus and tune the pion beam to send as many neutrinos as possible to the Super-Kamiokande detector.



The original design was based on the two-horn scheme at Brookhaven National Laboratory. After rigorous calculations and simulations of various shapes and sizes, the current three-horn design came about.

Balancing stress and performance

Building on the old neutrino beamline at Brookhaven National Laboratory (BNL), Ichikawa's conceptual design started out with two horns. The first horn would enclose a sapphire target, at which pions are produced. The second, larger horn would sit a few meters away to tune the shape of the pion beam.

It quickly became evident that the BNL style horns would not survive the heat and radiation load placed on them by the intense beam and the high current. To keep it cool, Ichikawa and her team would need to use sprays of cooling water, but even that would not be enough. The team needed some serious design work to reconsider the beam stresses felt at and around the target, and the shapes and the sizes of the horns.

"If we didn't have to think about the beam intensity, the original two-horn scheme would have worked," explains Ichikawa. The BNL style horns would ideally increase the neutrino numbers at Kamioka by a factor of about 17. "The idea was to design horns that have an efficiency of 95 percent of the BNL efficiency"

Ichikawa's study needed to balance the robustness and efficiency of neutrino generation at the horns. The high current flowing within the horns would produce high stress due to electromagnetic force—called Lorentz force—on the horns. The high intensity pulsed beam would give rise to strong thermal shocks and mechanical vibrations. She calculated the size and nature of all these stresses on the horns for various configurations, applied her simulations, modified the designs, and repeated the process.

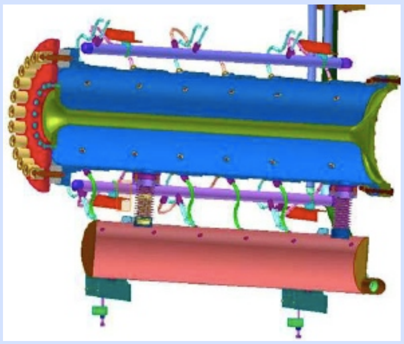
In particular, Ichikawa found that the two-horn configuration would not work. "The first horn is supposed to focus the pions, and the second one is to make the beam even," says Ichikawa. "However, the high intensity beam required an unrealistically large size for the horn." So she proposed to split the first horn to produce a three-horn system, in order to keep the size of the horns feasible for construction and handling.

Ichikawa surveyed the design of horns from around the world, such as ones at Fermi National Laboratory, CERN, and T2K's precursor KEK-to-Kamioka (K2K). Varying inner diameters, length, and curvature of the horn structure, she simulated as many as 600 different configurations.

One of the keys to a robust structure was to reduce the thermal and mechanical shock around the target. For the target, the team had chosen graphite instead of sapphire. Graphite has less dense crystal structure than sapphire, and therefore experiences less thermal load per volume. Ichikawa enlarged the inner diameter of the first horn to place space between the target and the horn's inner surface. The target is a cylinder of 90 centimeters long and 2.6 centimeters in diameter. The resolution was to expand the first horn's inner diameter from 1.9 centimeters to 6 centimeters. Since the magnetic field generated by the horn would decrease with the distance from the center, enlarging the inner diameter means reducing the stress due to the Lorentz force, as well as the thermal stress.

Horns to focus the world's most intense neutrino beam

The conceptual design was finalized in 2004, and the technical design was finalized in 2006. For Ichikawa, this was the first time she had done such engineering-oriented designs. She started out with no experience in building



This is an illustration of the inner component of the first horn, where the 90 centimeters long graphite target would be inserted.

radiation intense experiments but she had substantial experience in particle physics. Joined by Prof. Eric Zimmerman from Colorado University, Larry Bartoszek from Bartoszek Engineering, experts from Fermilab's MiniBooNE experiment, and a team of KEK engineers, Ichikawa successfully designed every single piece of the horn design.

"Since the target area is the most radiation intense area, everything needed to be made of ceramic or metal that are radiation-proof," explains Ichikawa. "We had to know for sure that none of the parts would fail, making sure the Lorentz stress, the thermal shock, mechanical vibrations, and aluminum corrosion were all under control."

If designing the horns to focus the world's most intense neutrino beam is a challenge, actually building them is another. From selecting the right vendor to managing parts under budgetary restrictions, she says everything was about challenge.

Support module to suspend the horns

In 2005, soon after the technical design phase started, another KEK member Dr. Tetsuro Sekiguchi, joined the team. Sekiguchi is the present leader of the horn team. For proper operation, the horns require precise alignment, a helium atmosphere, and a water cooling system. Sekiguchi had developed them to make those components work.

Each horn is suspended from the ceiling, hanging from an iron framework called a support module. The suspended design makes it easier to align the horns. The area which contains the horns, the helium vessel, is filled with helium gas to prevent contamination by air molecules that can interact with pions and cause radiation contamination. Sekiguchi designed and developed the support modules and most of the crucial components around the horns.

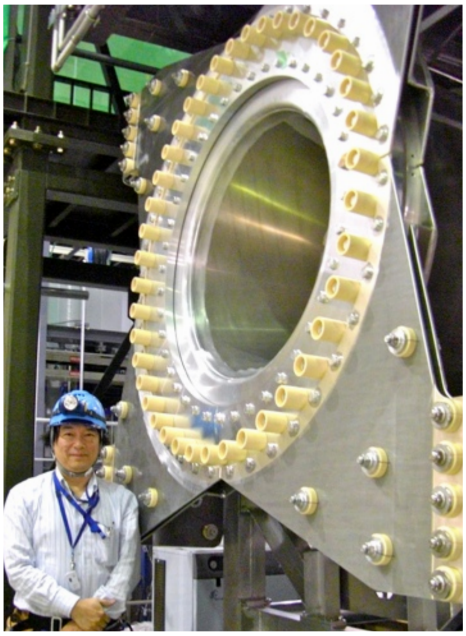
"The challenge was to install and maintain the horns in strong radiation environment," says Sekiguchi. "Everything needs to be remotely controlled with cranes to a 3-millimeter precision." Blocks of one-meter thick concrete and three-meter thick iron sit above the service pit to shield human operators from dangerous radiation.

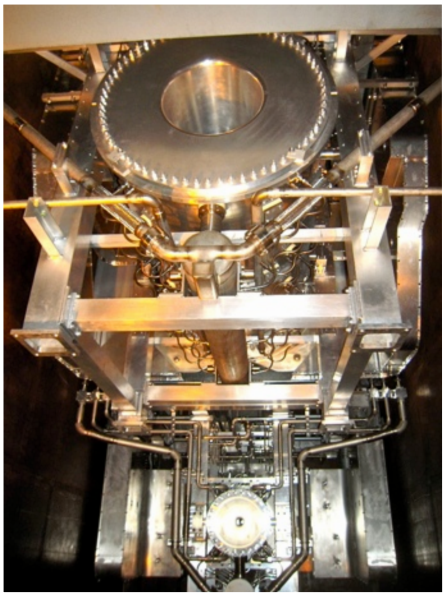
For maintenance, the horns and their support modules are brought to the maintenance area. However, before the horns can be moved, they first need to be dismounted from the iron shields. Operators can stand on the support module only when the thick blocks of iron and concrete are in place. So for the operators to detach the support modules from the shields, they must stand on top of the blocks and remove bolts four meters below them through four-meter long shafts with a four-meter long wrench.

As your everyday experience will tell you, making bolts four meters away tight and straight is not easy. To make this work, Sekiguchi and his team discussed and produced a design that would make the bolts fit correctly no matter what angle they came in. This specially designed assembly allows operators to attach and remove the bolts on the support modules through a narrow four-meter vertical shaft. "It was this type of small detail we had to address when we made our designs," says Sekiguchi.

Developing the support module was a tricky business as well. Because of the strong radiation from underneath, the massive blocks of the iron shield need to fit as tightly as possible. However, they cannot be too tight, or installation would be impossible. The space between each block was designed to be at 3 centimeters, but came out to be much narrower when actually constructed: about 1 centimeters and even 5 millimeters at the narrowest point.

The largest horn, the third horn, is an eight-meter tall object. Consider installing an eight-meter object with 5-millimeter precision without a single scratch using the huge arms of cranes. "We've been monitoring the installation process with camera," says Sekiguchi. For now, that works, but not well. The team is now constructing a new guide system to ensure the safe installation in millimeter precision.


Prof. Yoshikazu Yamada of KEK, the leader of the secondary beamline (the target station, the decay volume, and the beam dump), stands in front of the third horn before installation.


The first horn (below) and the second horn installed in the target station.

Milestones: the beating horn and installation

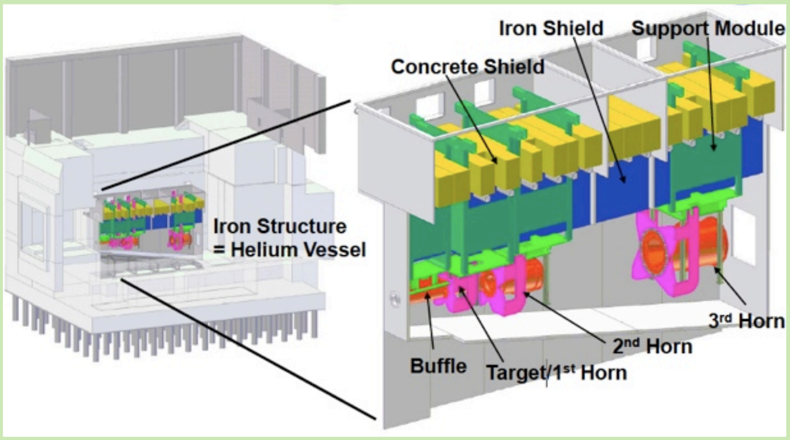
In June 2006, the prototype horn was first electrified. "It was a sensational moment," recalls Ichikawa. When the pulse of the electrical current flow in the horn, the Lorentz stress on the horn created huge sound. Every few seconds came a BANG sound that was unbearable to naked ears. "Despite all the troubles we had had up to that point, the test operation gave us confidence that we were on the right track." The team's careful and thorough design process had brought about a smooth test run.

The test operation was conducted with the horn sitting on the floor. Actual horns were to be hung below the iron support modules. Sekiguchi and Ichikawa worked together to complete the support module testing at KEK, and to construct the second horn in the US and the third horn in Japan.

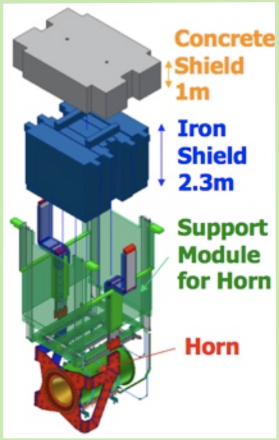
Installation of the horns marked the second big milestone for the team. Due to a one-month delay in the construction of the building, schedules were pushed back. In order to recover the delay, many devices had to be installed simultaneously. "We worked night shifts to optimize the crane use," recalls Sekiguchi.

Horns in operation

T2K has been in full operation for a few months now. The first neutrinos were observed at the near detector late last year, and the first neutrinos are expected to be observed at Super-Kamiokande within a few months. So far, the horns have operated exactly as hoped.



The three horns are suspended from support modules inside the service pit at the target station. Thick blocks of iron and concrete sit above the service pit to shield human operators from dangerous radiation.



A horn hanging from a support module. Above the support module are the concrete and iron shields which make the area above safe for humans to walk on it.

However, to stabilize the horn operations is still a challenge. Sekiguchi says there are many things to take care of to ensure continued stable operation.

The first is the cooling water. A mist of water continuously showers the horns to keep their temperature below 60 degrees Celsius so not to cause deformation of the aluminum. The runoff is gathered in tanks and pumped back up to the surface level. “Either too much or too little water can cause problems in the experiment,” says Sekiguchi. If there is too much water, it will interact with the pions, reducing the number of neutrinos produced, and at the same time becoming radioactive. If there is too little water, the horns will overheat. “Adjusting is especially hard when water needs to go 8 meters up and down.”

The second concern is the vacuum level inside the service pit. The entire pit is filled with helium gas so pions would not interact with air molecules. However, water can interact with pions and produce hydrogen and oxygen. Those hydrogen molecules are combustible and could become dangerous, but they cannot be easily disposed of because they are radioactive. The team is currently developing a damping machine for hydrogen.

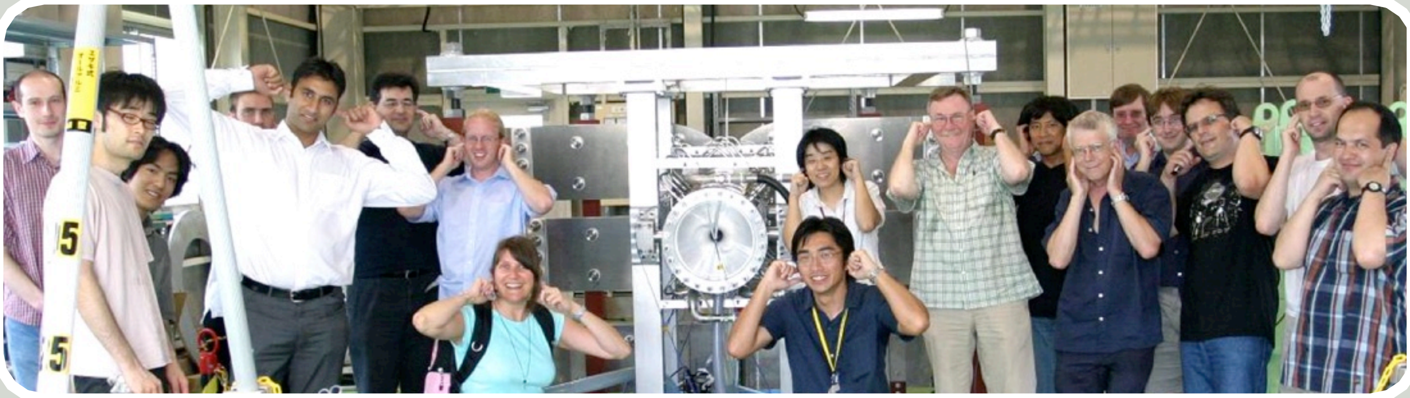
For a system that was so large and complex, a test-and-modify approach was not possible. All designs and development were created and installed in one-shot. “I think all the bugs have come out in these two years. Now we are working on solutions,” says Sekiguchi.

Sekiguchi also mentions that the key to stable operation right now is the stable power supply. The current power supply was a hand-me-down from the K2K experiment, and has already failed once in the six months before the operation started. Sekiguchi and engineers at KEK are working on a brand new, low-noise power supply that can produce a 320 kilo-Ampere current with stable pulse widths of 0.3 percent precision.

The physics is near

Ichikawa and her students at Kyoto University are now refining the simulation she began ten years ago. To determine the properties of neutrino oscillation, the collaboration needs to simulate every component of the experiment and particle beam. In particular, beam simulator will calculate energy and number of particles such as muon, proton, and neutrinos. Ichikawa and her colleagues work on the neutrino beam component. They will provide neutrino information such as neutrino types, energy, and number, at the near detector and Super-Kamiokande.

“I am looking forward to seeing the physics that result from this experiment,” says Ichikawa. The oscillation analysis will be ready by August of this year. Asked why she had dived in the T2K experiment, she answers, “I like working hard towards one goal.”



The excitation of the prototype horn ended in success. Every few seconds, when an electric pulse hits the horn, the horn makes a loud sound which is painful to human ears.

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