December 1, 2009

Art of mapping neutrino 3D trajectory

[Neutrino, Time Projection Chamber, Micromeagas Gas Detector]

The time projection chambers (TPCs) are important components of the near detector at the Tokai-to-Kamioka (T2K) neutrino experiment. They are designed to identify the types of particles passing through the detectors and measure their momenta. The T2K TPCs are a new design, the product of innovative ideas from Europe and Canada.

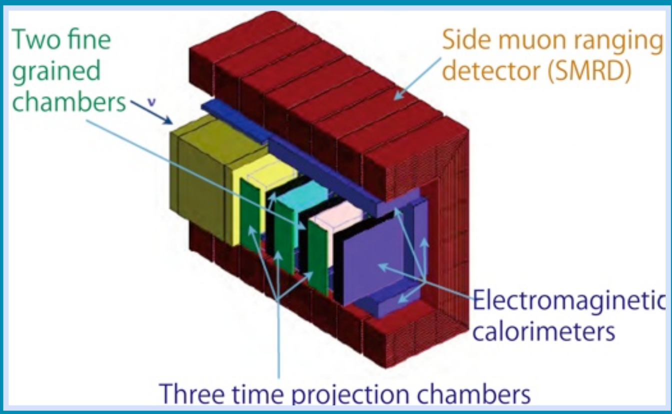
From right: Prof. Dean Karlen of the University of Victoria and TRIUMF. A postdoc Dr. Kendall Mahn, from TRIUMF, and a PhD student Casey Bojechko, from the University of Victoria, are working on T2K TPCs.

On November 24, physicists from the Tokai-to-Kamioka long baseline neutrino oscillation experiment (T2K) announced the detection of the first neutrino events. Neutrinos produced from 30 GeV protons were detected in one of the T2K near detectors (ND280), INGRID. With the milestone, the T2K experiment has entered into the operational phase. The physicists are now working towards completion of installation of the near detectors in preparation for the full-scale startup next month.

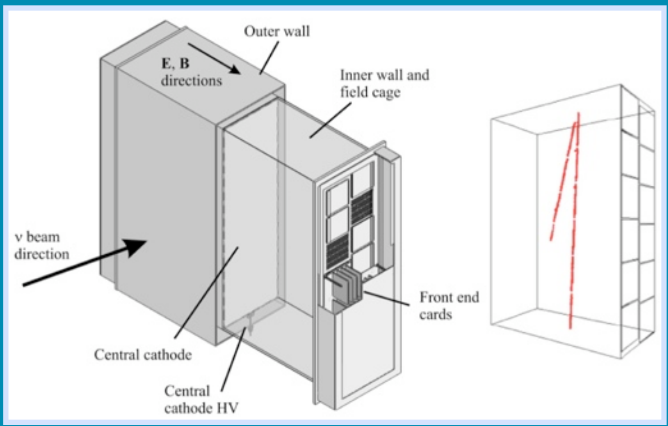
The goal of the T2K experiment is to study neutrino flavor change, more commonly known as neutrino oscillation. Neutrinos have three flavors: electron-, muon-, and tau-neutrinos. Differences in the masses of neutrinos cause them to periodically change flavor. The T2K experiment aims to discover the muon-to-electron neutrino flavor change.

To do this, physicists produce a beam of muon neutrinos at Tokai, observe the characteristics of the beam just after production at a set of near detectors, ND280, then send the beam 295 kilometers to Kamioka underground to again observe the beam at the water tank neutrino detector, Super-Kamiokande. By comparing the two observations, physicists can determine the changes in the beam as it travelled between the two locations.

The neutrino beam produced at J-PARC spreads out like a cone. Super-Kamiokande observes neutrinos coming out 2.5 degrees from the beam center. This is called an 'off-axis' configuration, because the neutrinos being measured are off the main axis of the beam. Physicists chose this configuration to narrow down the energy distribution of



The T2K ND280 magnet (red) contains a basket of detectors, in which a pi-zero detector, two fine grained detectors, three time projection chambers (TPCs), and an electromagnetic calorimeter line up.



(Left) To fit in the basket, the TPCs have a cross section of 2.5 meters square, and in the beam direction, the dimension is 0.9 meters, a depth chosen to achieve momentum resolution. (Right) Three-dimensional reconstructed signals of cosmic rays used to check for miswiring.

Prof. Toshifumi Tsukamoto of KEK standing in front of the T2K's ND280 off-axis before the installation of sub-detectors in the basket. He acts as a liaison to the foreign groups of T2K near detectors.

neutrinos in the beam to the range where neutrino oscillations would most likely occur at the far detector.

Because of this configuration, there are two detectors in the T2K experimental hall. One detector, called INGRID, is on the main beam axis, while a second detector, called ND280 off-axis, is located 2.5 degrees off the main beam axis. INGRID measures the profile and flux of the on-axis beam, and ND280 off-axis measures neutrino flux and energy spectrum of the off-axis neutrinos which head to the Super-Kamiokande.

Composed of 80 percent international researchers, T2K is the largest international project at the Japan Proton Accelerator Research Complex (J-PARC). J-PARC is a high-intensity proton accelerator facility constructed jointly by KEK and the Japan Atomic Energy Agency (JAEA). About 500 members from 12 countries—Canada, France, Germany, Italy, Japan, Korea, Poland, Russia, Spain, Switzerland, UK, and US—have contributed to the T2K project over the past 6 years.

"The current range of international collaboration at T2K owes much to the hospitality of KEK and its staffs' great efforts," says Prof. Tsuyoshi Nakaya of Kyoto University, the leader of near detectors team. Prof. Toshifumi Tsukamoto at KEK, who acts as a liaison to the foreign groups of T2K near detectors, is one of the most important persons to lead the successful installation of near detector systems. "The success is the result of the professional work of individuals, the conscientious supports by KEK staffs of the neutrino group, and the great teamwork of international groups who respect each other."

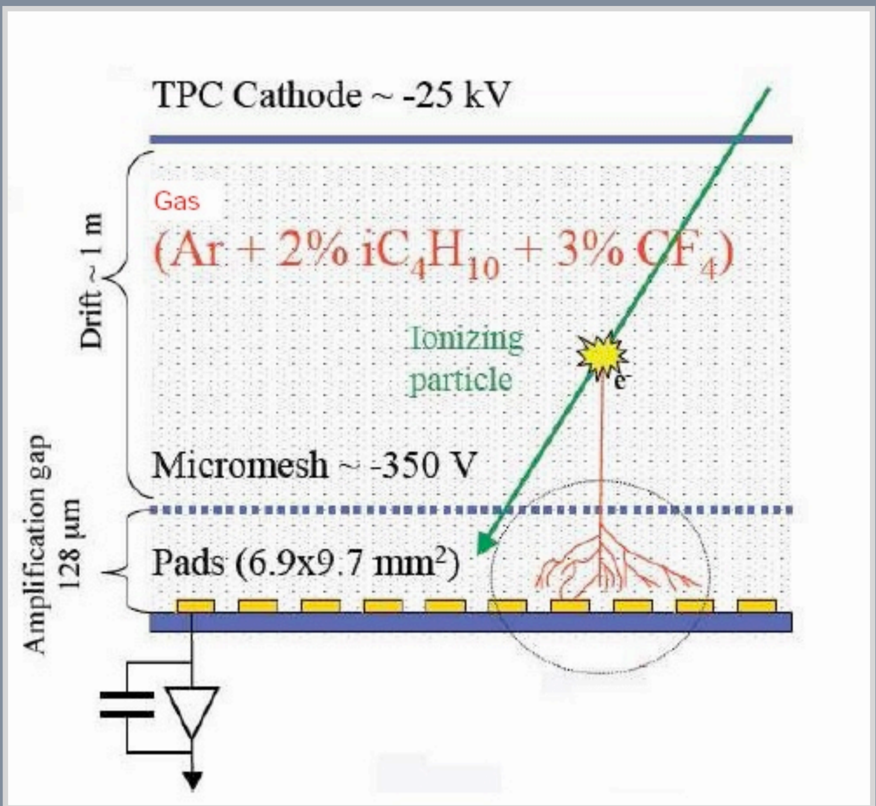
Even in such an international collaboration, T2K's Time Projection Chamber (TPC) group is unique. For one thing, it is the only group that is composed of non-Japanese multi-national collaborators. Including approximately 80 researchers from Canada, France, Germany, Italy, Spain, and Switzerland, the group makes up a large part of the T2K ND280 collaboration. Secondly, it is the only detector component in the two near detectors that does not employ scintillators and photo sensors. All other detector components use new photo sensors called multi-pixel photon counter, MPPC. These sensors are an important new technology developed by Hamamatsu Photonics and KEK-T2K collaborators (featured in a previous story).

Time projection chamber

A TPC provides a 3-dimensional picture of the path of charged particles passing through the chamber with a fast, electronic read-out system. At T2K, there are three TPCs in a five-layer sandwich with fine grained detectors (FGDs) in between. These layers of TPCs and FGDs are placed in between a pi-zero detector (P0D) and an electromagnetic calorimeter (ECAL). A small fraction of neutrinos interact and produce particles in the FGDs. TPC modules are designed to distinguish types of those resulting particles and measure their momentum and charge.

On the insides of the TPC boxes, there are copper strips on panels and resistors that connect them to create a uniform electric field inside the box. A cathode plate stands parallel to endplates to divide the box into two. When particles pass through the chamber, the mixture gas of argon, iso-butane, and carbon tetrafluoride liberate electrons through ionization process. These electrons drift to the ends, and are measured by modules called 'micromegas'. Physicists use the data to reconstruct the trajectory of the particles.

The TPCs will operate inside the large ND280 magnet transported from CERN to J-PARC. The magnet was previously used for UA1 and NOMAD experiments. Charged particles bend in the magnetic field and the curvature of the tracks tells the charge and momentum of the particles and the amount of ionization identifies each type of the particles. "The TPC is excellent at separating muons from electrons,



Schematic view of micromegas, the new technology to detect electron ionization signals. T2K's TPC is the first large scale application of micromegas.

and therefore can separate muon neutrino events from electron neutrino events," explains Dr. Kendall Mahn, a postdoc with TRIUMF in charge of the TPC test.

The original research and development of TPC was for the next-generation linear collider, the International Linear Collider (ILC). "In 2004, we realized that this type of detector could be used in the near detector for T2K and the T2K collaboration approved the concept," says Prof. Dean Karlen who holds a joint appointment at the University of Victoria and the TRIUMF laboratory in Canada.

Karlen says that there are three innovative features in the design of the TPCs: the mechanical structure of the TPC, the gas amplification system, and the calibration system.

Mechanical structure of the TPC's

The TPC has a double box design. An outer wall surrounds the main body of the TPC, including the endplates. The space between the inner and outer walls is filled with carbon dioxide gas. This helps to insulate the central cathode from the outer wall, and also reduces contamination of the drift volume by air molecules.

"The panels of the inner box are composite with copper clad skins and sturdy foam core. The strips to create the uniform electric field were made by machining away copper material," says Karlen. "This allows for a very precise alignment." The panels and the other large components were machined and assembled using specialized equipment and facilities at TRIUMF.

'Wireless' TPC

The T2K TPC is the first large scale TPC that does not use individual wires to detect the electron ionization signals. Although wire amplification can produce higher gains, the wire spacing is limited to several millimeters which can limit the capabilities of the detector. Also, the narrow wires used in such chambers can break as a result of a spark. With a wireless TPC, most of the positive ions produced in amplification are collected immediately instead of lingering around and so do not distort the electric field.

T2K uses technology called 'bulk micromegas', micropattern gas detector (MPGD) to amplify the electron signals before they are sampled by readout pads. Micromegas is composed of the readout pads and a thin wire mesh placed just 128 microns above them.

The micromegas modules were produced at CERN, under the responsibility of the CEA/DAPNIA (Saclay) Laboratory in France. "Because T2K TPCs are the first large scale application of the bulk micromegas, a lot of R&D work was necessary to prove these detectors had the ability to fulfill the T2K requirements," says Claudio Giganti, a PhD student at Saclay.

Each of the 24 modules for each TPC underwent rigorous tests at CERN. To test if the energy resolution of each module is satisfactory, Giganti and his colleagues mounted each module in a small chamber filled with a gas, and exposed it to an iron source that emitted 5.9 keV photons. Only those modules where each of the 1,728 channels of detectors fulfilled the energy resolution requirement passed the test. These modules were installed on the TPC endplates.

The micromeagas were then brought to TRIUMF and installed in the TPCs, and tested with the electron, proton, and muon beams. Giganti says that the tests were all successful.

Apart from the detector itself, many efforts were put into the electronics that read the TPCs. The front-end electronics are also Saclay's responsibility. One endplate has 20,000 channels of electronics each of which measures the amplitude of electrons and the time of arrival. "It was difficult to arrange the electronics in the small space allocated, because the three TPCs altogether consist of 120,000 channels, and taking the read-out data from all channels combined is a difficult task," says Giganti.

Photoelectron calibration system

In order to monitor the shape of the electric and magnetic fields within the TPC's, physicists from Canada developed a calibration system. Aluminum targets were placed on the central plate of the detector. Physicists then used a pulsed ultraviolet laser to knock photoelectrons off of the aluminum targets. The laser was tuned to just the right energy to kick out photoelectrons from aluminum, but not from copper, giving a nice, clean image of the targets.

The photoelectrons then drift through the detector and are read out by the electronics. "The process is very similar to how electrons created by charged particles work," explains Casey Bojechko, a PhD student from University of Victoria. A well defined pattern of

Bojechko applying aluminum targets on one of the central cathodes for field calibration system.

Claudio Giganti is a PhD student from Saclay National Laboratory in France, working on micromeagas component of the TPC.

Mahn is working to help start up the data acquisition system and install the last TPC. She and her colleagues are planning to improve the measurement of electron neutrinos with the TPC. Giganti is helping to integrate the frontend electronics for the micromegas. Having developed the particle identification methods with TPCs last year, he will also work on the Monte Carlo analysis for the measurement of the electron-neutrino component of the beam.

"This is a very exciting period for us. We will soon start the beam and see the first neutrino events," says Bojechko. "Things are coming together quite nicely. It is nice to be in an environment like J-PARC where everyone is committed to a common goal."

Further commissioning of the detector and integration of the detector with the rest of ND280 is underway. "I look forward to the completion of the near detector installation and commissioning, and the initial physics data taking for the T2K experiment," says Karlen. Over the coming 5 years, they hope to collect significant data which could transform the understanding of neutrino physics.

"This particular physics program is quite exciting, and working with a new, cutting-edge type of detector is really fun," says Mahn. "The hardest part is stopping myself from getting involved with too much!"

photoelectrons produced inside the TPC drift the full distance.

If field non-uniformities are present, the test pattern will not match the expected pattern. The direction and magnitude of the non-uniformities can then be calculated from the differences in the two patterns.

"The first test of the calibration system worked only marginally," Bojechko says. Some of the aluminum calibration targets were not producing any electrons, while others were working as expected. The team noticed that the targets that had undergone more cleaning were the ones working normally.

The solution to this problem was simple but tedious: clean each target yet again, this time using extraordinary care. In the second cleaning, the calibration targets were cleaned multiple times with two different chemicals: isopropyl and ethanol. Bojechko cleaned each target—as many as 4,000 of them—with cotton swabs several times. "It took us almost three weeks," says Bojechko. "After the cleaning the calibration system started working very well."

Final step

Two TPCs are already installed into the underground ND280 off-axis detector basket. The final TPC has completed a successful test at TRIUMF, where the team used a beam of protons, muons and electrons to test the response of the detector. It is now in Japan where the team prepares to install it in the basket.

"It is great to see that the TPCs work so well in tests," says Karlen. "The time scale from initial concept to installation has been very short for such a complex device. The rapid progress we have made is due to the exceptional dedication to the project by the members of our team."

Now, the team is working on the final tunings in preparation for the physics that starts next year.

2 TPCs and 2 FGDs were successfully installed in the ND280 basket in early October.

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