（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）
国外連携機関長期研修　報告書

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I stayed at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) from October 2021 to March 2022 and worked on collaborative research with local colleagues. I will summarize the activity below.
My colleagues and I belong to the T2K experiment, which is a long-baseline neutrino oscillation experiment conducted in Japan. We generate neutrino beams at the J-PARC accelerator and detect them at both the near and far detectors. The near detector is located 280 m downstream from the beam target. The far detector, well-known as Super-Kamiokande, is located 295 km downstream. The ultimate goal of our experiment is to search for the CP violation via the precise measurements of neutrino oscillation. So far, T2K has reported a result that disfavors the conservation of CP with a confidence level of 2 sigmas [1]. Our next challenge is to try to measure the CP violation with a 3-sigma confidence level. To achieve that goal, we are currently planning to upgrade our near detector called “ND280”. ND280 is composed of several target and tracker detectors as shown in Figure 1. In the upgrade of ND280, we will replace the Pi-Zero Detector (P0D) with new a scintillator detector and two horizontal Time Projection Chambers (TPC). The new scintillator detector is called Super Fine-Grained Detector (SuperFGD) and it is composed of approximately 2 million scintillator cubes with a size of 1 cm^3 as shown in Figure 2.

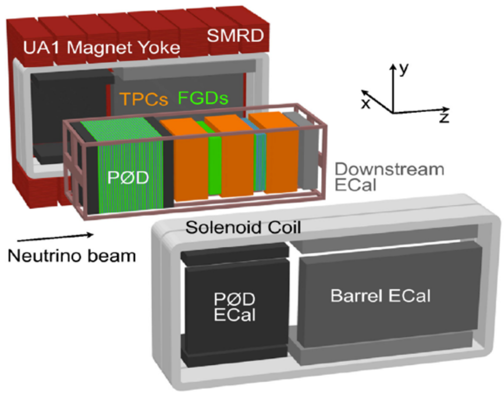

Figure 1: T2K near detector ND280

During my stay at ETH Zurich, I worked on the development of the software that will be used for upgraded ND280. The main progress of the research is as follows:

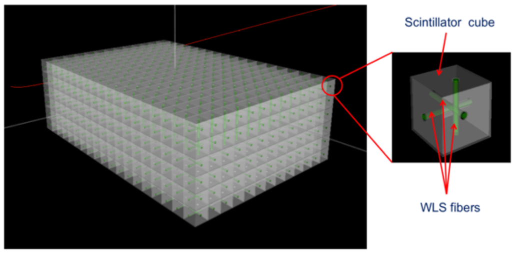

Figure 2: Schematic view of SuperFGD

1) Integrated trajectory reconstruction of detectors including SuperFGD.
To precisely measure the properties of neutrinos, we try to detect the types and kinematics properties of charged particles that are produced by neutrino interactions. Since what we get from the detectors are just electronic signals, it is important to reconstruct the trajectories of charged particles from signals. In the past SuperFGD-related analyses, we were only focused on the tracking of particles stop inside SuperFGD. However, when charged particles are produced inside SuperFGD, many of them escape from SuperFGD. For these escaping particles, we need to combine the reconstruction of several detectors. During the stay at ETH Zurich, in cooperation with the experts of other detector software, we have implemented the matching and re-fitting of these reconstructed trajectories between detectors. We also performed various types of validation studies to confirm that the new detector-integrated reconstruction works as expected. We have completed this and now we can perform an integrated analysis using this information.

2) Development of software for the high-level analysis of near detector data.
After taking data using the near detector and reconstructing tracks, we perform a variety of analyses using software called HighLAND (High-Level Analysis for Near Detector). Since we will install new detectors, some

modifications were needed to run HighLAND with an upgraded set of near detectors. In parallel to the development of integrated reconstruction between detectors mentioned above, I worked on the development of a converter that converts the information obtained from the trajectory reconstruction into an analytical format. In addition, I created a new set of analysis packages for the upgraded ND280 analysis that will be used as the baseline for upgrade analysis. Using these packages, several collaborators are now actually working on the development of their event selection and analysis studies.

3) Development of analysis methods using deep-learning tools.
In a corporation with a computer scientist at ETH Zurich, we studied the possible application of deep-learning tools to SuperFGD analysis. We mainly used the convolutional neural network (CNN) for our studies. CNN is a well-known neural network method that is often used for image classification. Since SuperFGD has a very finely segmented structure, I thought that CNN could be applied by considering each cube as a pixel of a neural network. Although I was not an expert in machine learning techniques, I was able to start this project with the help of a computer scientist at ETH Zurich. The main focus of these neural network applications was the particle identification (PID) of reconstructed tracks. The biggest problem of the CNN application to the SuperFGD data was input data handling. Since SuperFGD has approximately 2 million cubes, it is computationally too heavy to give all the cube information to the network for all the input events. After many trials and discussions, we adapted Submanifold Sparse Convolutional Network. Thanks to the fact that in most cases SuperFGD has a very sparse hit structure as shown in Figure 3, we were able to reduce the computation. After the development of the network structure and many trials of optimizations, we found that we can achieve better PID performance compared to the standard traditional PID methods we have developed so far. We are also working on the validation and preparing to publish these results in a paper soon.

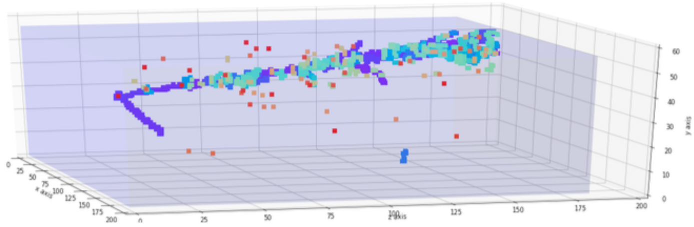
Figure 3: Example of event display

[1] The T2K Collaboration. Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations. Nature 580, 339–344 (2020). https://doi.org/10.1038/s41586-020-2177-0
[2] Benjamin Graham, Laurens van der Maaten, Submanifold Sparse Convolutional Networks. 2017. https://doi.org/10.48550/arXiv.1706.01307


Figure 4: A view of office after a discussion using a blackboard