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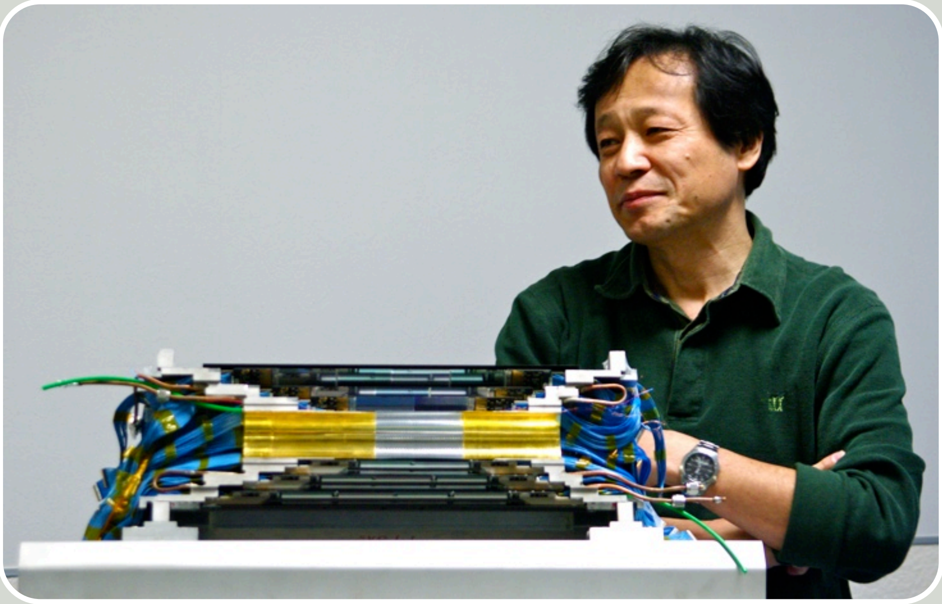
FEATURE STORY



Prof. Junji Haba of KEK, the head of Detector Technology Project, is also a technical coordinator for Belle experiment. The silicon vertex detector (front) is the inner most detector of Belle, and underwent many revisions.

Detector technology project connects fields

[Cutting-edge Detector Technology, MPGD, DAQ, SOI, STJ, TPC, ASIC, QPIX]

It has been almost five years since the launch of the Detector Technology Project (DTP) at KEK. In that time, this new entity has established vital cross-project connections within KEK and beyond, and helped to develop a number of promising new technologies.

In 2005, Prof. Junji Haba of KEK launched the Detector Technology Project (DTP), receiving a strong support from the then director of Institute of Particle and Nuclear Studies at KEK, Prof. Fumihiko Takasaki (now an Executive Board member). Haba's goal was to improve the strength of Japan's detector technologies by establishing a common base for detector development at KEK. This, he thought, would bring about a number of advantages: introduce Japan's frontline technologies to the world, foster cross-disciplinary collaboration, establish domestic bases for technologies critical to sciences using particle beams, and encourage as well as simplify detector research and development activities.

“In Japan, detector technologies had been developed on a project-by-project base. The importance of integrating detector technologies and know-how had been neglected,” says the DTP head Haba. “Europe and the US have accumulated knowledge of detector sciences, and have held strong traditions of detector systems.”

Almost five years into the project, Haba's scheme has worked out quite nicely. Japan has strong technological bases worth being introduced to the world, such as the silicon on insulator (SOI) technology, an innovative device that integrates sensor and readout electronics in a single piece. The project has also built inter-university collaborations for studying and developing a new photo sensor called MPPC, which are now installed in the detectors at the long-baseline neutrino experiment, T2K. The DTP has established horizontal collaboration on detector technology, bridging large and small projects from particle physics, nuclear physics, and material sciences.

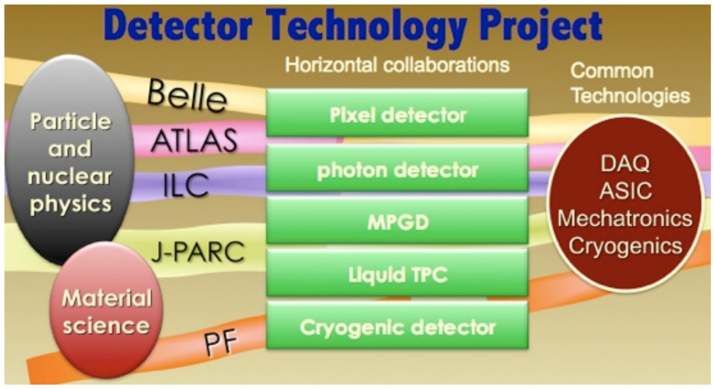
Currently the DTP has seven projects: micro pattern gas detector (MPGD), data acquisition system (DAQ), silicon on insulator (SOI), superconducting tunnel junction device (STJ), liquid time projection chamber (TPC), application specific integrated circuit (ASIC), and photo sensors.

“Each project has its own directionality, but each also furthers one or more of our four central goals: to promote applications of detector technology to other disciplines, to lead the world with cutting edge technologies, to establish solid bases for existing technologies which are currently missing or insufficient at KEK, and to promote collective and collaborative research and development activities among universities and research institutes.”

Basic principles of particle detection

There are hundreds of types of subatomic particles of interest. Such particles include elementary particles like neutrinos, composite particles like B mesons, and force carriers like photons. All of these particles are unimaginably small, and many move very fast.

The basic principle of particle detection remains pretty much the same since the very first days of particle detectors. When particles pass through a material, they interact with surroundings either emitting light or knocking electrons loose from the atoms or molecules near the particle's path (ionization). To detect light, scientists use photo sensors. In ionization detection, the electrons knocked loose are carried to sensors by an applied electric field.



The Detector Technology Project aims to build horizontal collaborations and empower the research and development of the common technologies.

The information that physicists can derive from these sensors depends on the geometry and capabilities of the sensors. Sensors can collect information about such things as position, the time at which an event occurs, and the number of particles. Readout electronics are generally attached to the rear side of the sensors. These electronics then output the data to computers for analysis. In a nutshell, the basic design of a detector involves choosing the types of the media which particles traverse and ionize, the type of sensor, and the design of the electric readout system.

MPGD's many applications

The DTP has already made fruitful contributions to many experiments by bridging multiple disciplines studied at KEK and the Japan Proton Accelerator Research Center (J-PARC). One particularly notable project is the micro pattern gaseous detector (MPGD) project.

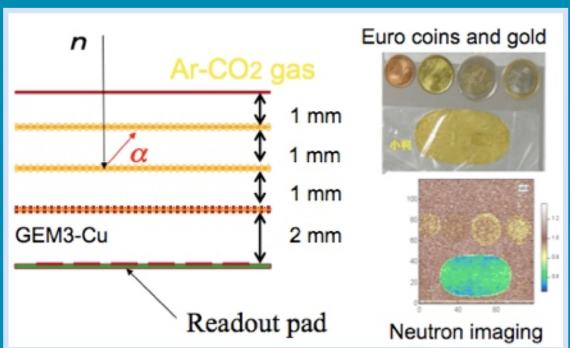
MPGDs are fast, high performance, position sensitive sensors designed for two-dimensional gaseous detectors such as gaseous time projection chambers (TPC). A gaseous TPC is a box filled with a noble gas—generally argon or helium. Particles passing through the gas ionize the atoms of the gas. An applied electric field causes the resulting electrons to drift towards sensors on the sides of the chamber. However, the number of electrons created by ionization is relatively small, around 100. Since the background noise count can be as many as 1,000, it's very difficult to identify signals from the background.

The way to resolve this problem is to amplify the signal electrons. In the vicinity of the sensors, physicists apply an electric field about 100 times stronger than that in the chamber, and accelerate the signal electrons. These electrons become energetic enough to kick out additional electrons from atoms, and those additional electrons are accelerated again to knock out still more electrons from other atoms. When the avalanche of electrons finally hit the sensor, a single electron is amplified to 10,000 electrons.

There are several types of MPGDs studied around the world. The MPGD project at KEK studies a type of MPGD known as a gas electron multiplier (GEM). The GEM was first introduced at CERN in 1996. (Another type of MPGD called micromegas is used for the TPC chambers in one of the T2K's near detectors, which is featured in the article here.)

A GEM is essentially a sandwich, with thin copper foil electrodes as the bread, and a polyimide insulator as the meat. Arrays of small holes (around 70 micrometers in diameter) are punched through the sandwich. Lastly, an electric potential of 320 volts is applied across the sandwich, and this voltage is what accelerates the electrons and amplifies the signal. Because each hole on the GEM foil can identify signals, the sensor can report two-dimensional information on one event.

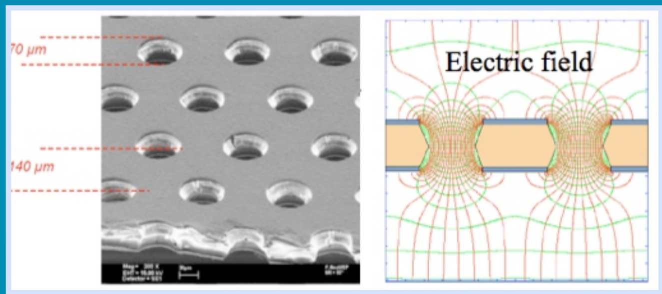
Although the technology was invented for particle and nuclear experiments, the MPGD collaborators have found various applications in material and life sciences as well.



(Left) The gas electron multiplier (GEM) foil can image two-dimensional position of particles passing through a gaseous chamber. (Right) The cross sectional view of the GEM shows strong electric fields in the vicinity of holes where electron signals are amplified.

At the J-PARC neutron facility, the use of GEM's has made two-dimensional imaging possible, resulting in better position and time resolution. To detect neutrons, the team coated GEM foils with a neutron-sensitive material, boron. When a neutron hits the boron coating, it produces an alpha particle whose charge triggers the detector signal. The boron coating is inexpensive compared to the very rare isotope of helium (He-3) used for conventional neutron detectors. Also, since boron is sensitive to neutrons but not to gamma rays, it eliminates background noise from gamma rays. Using this technology, the scientists at the neutron facility were able to gain remarkably clear two-dimensional images of the gold content in coins (see image).

GEM's application does not stop there. If coated with X-ray sensitive materials, a GEM becomes an excellent X-ray detector. For example, this can be used to image iron bars deep inside a concrete block, and might bring about a new tool for construction inspection. The collaborators also study applications to medical equipment such as single photon emission computed tomography (SPECT).



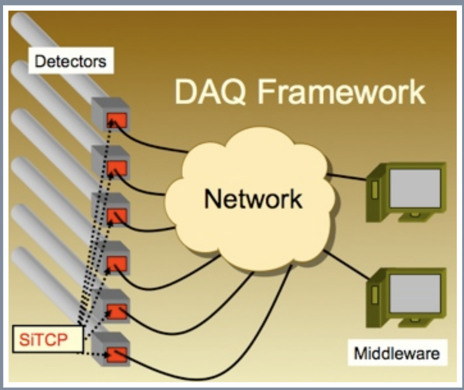
Each GEM foil (orange) is coated with boron so as to make them sensitive to neutrons. Several neutron groups at J-PARC have employed GEMs for their detector. The right shows a neutron image of gold.

Standardized electronics

KEK's new data acquisition (DAQ) framework is another notable result of the cross-discipline collaboration fostered by the DTP. The new DAQ was developed by KEK physicist Dr. Tomohisa Uchida, and is now widely being employed. The goal of the DAQ system is to readout data from detectors and send it to a computer as fast as possible.

"Our motivation was to use currently available advanced network technology to make data acquisition simple and fast," explains Haba. The technology they used was the standard transmission control protocol (TCP) that every computer uses to connect to the Internet nowadays. The team developed a silicon TCP (SiTCP) circuit that can talk network language and programmed it into a field programmable gate array (FPGA). An FPGA chip is then placed in each detector so that each detector can be directly connected to a network via an Ethernet cable.

"This way, we do not need individual CPU's inside each detector. All users have to do is to



The newly developed silicon TCP (SiTCP) simplifies data acquisition process from detectors to computers.

connect the detectors to a hub with Ethernet cables, and they can then start analyzing data in a LabVIEW like environment."

A middleware—computer software tool connecting application software—called robot technology (RT) middleware was specially designed by National Institute of Advanced Industrial Science and Technology to offer user interface to view and analyze the output data. The DAQ-middleware framework brings about almost a plug and play capability.

"DAQ-middleware is very useful to small projects that cannot afford a DAQ expert," says Haba. The SiTPC technology has already found several applications. All GEM detectors developed in MPGD project are equipped with the DAQ. Other applications include Hadron Hall at J-PARC, the neutrino detector Super-Kamiokande, and the CCD readout system for the hyper supreme camera at the National Astronomical Observatory of Japan.

SOI: Japan's leading detector technology

Including 70 collaborators, 20 of whom are international, the silicon on insulator (SOI) project is the largest international project in DTP. SOI is a high-resolution, fast and low power sensor currently studied only in Japan. Since 2005, the SOI project has collaborated with Oki Electric Industry, a Japanese company that has strong SOI technology.

Ordinary computer chips have a silicon substrate which is several hundreds of micrometers in thickness. Because of the thickness, small parasitic capacitances can form within it, and can degrade the performance of the chip. SOI inserts an insulator between the circuit and the silicon substrate to eliminate the device capacitance, and unnecessary currents flowing in the silicon area. The fast, low current SOI is a widely used technology in the semiconductor industry today.

However, what detector scientists saw in the SOI was not a semiconductor but a sensor. "We can use the silicon as a sensor, and the readout circuit is conveniently attached just 1 micrometers away, completely insulated," says Haba. "It is an all-in-one technology." Because the conventional detectors and readout electronics are separate entities, they must be connected by bonding, and the solder bumps for bonding cost at least 50 micrometers of space. With this innovative technology, scientists can skip the bonding, and greatly reduce the amount of material required to construct a sensor. Less material means less disturbance to particle paths, and the better performance in particle physics experiments.

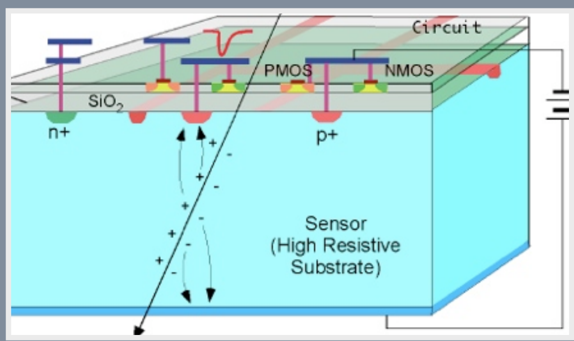
The thickness of silicon is also scalable. For example, high energy X-ray detectors need substantial thickness. If they are too thin, the X-rays will simply pass through undetected. Detectors which use standard charged coupled device (CCD) technology are limited in their thickness by the nature of the technology. This limits their ability to detect high-energy X-rays. The SOI detector can be made as thick as desired to absorb and detect high energy X-rays.

Aspiring for unseen energies

Another anticipated technology is called superconducting tunnel junction (STJ). In superconductors, electrons travel as pairs. These pairs, called Cooper pairs, are responsible for the superconducting state. However, the pairs are fragile, and just a few milli-eV of energy can destroy them. Detector scientists plan to use this property to detect particles of very small energy. "The STJ will be a breakthrough when realized," says Haba.

The new cosmic microwave background (CMB) radiation group at KEK is in the middle of research and development of an STJ detector to detect primordial gravitational waves in the CMB. A different group, this one led by Prof. Shinhong Kim of Tsukuba University, is seeking a way to detect the neutrino decays thought to occur abundantly in our universe. Through these projects, the STJ may help to answer the most profound questions about our universe.

All these teams have many challenges to overcome. The project has built a clean room where they can produce their own detector samples in-house. The CMB group is yet to observe their first signals. Observing neutrino decay will be even more challenging, because this project requires their STJ to sense photons with an energy of just a hundredth of a thousandth of an eV. To create a superconducting state sensitive to such low



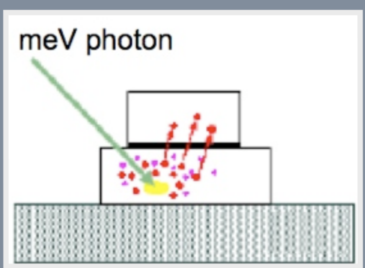
Silicon on insulator (SOI) combines sensor and circuit in one detector.

energy photons, the team first needs to figure out a way to keep material stably at 0.05 Kelvin.

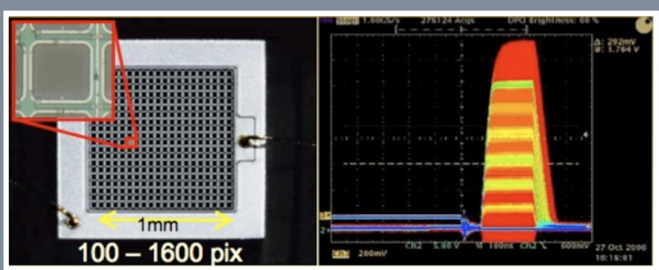
Complete four-dimensional imaging

The current neutrino observatories detect Cherenkov photons. These are photons emitted by particles that result from interactions of neutrinos with a medium. The neutrino interactions produce both photons and other particles. However, because current observatories can only detect photons, they cannot distinguish between different types of neutrinos. This might change forever in the advent of liquid TPC.

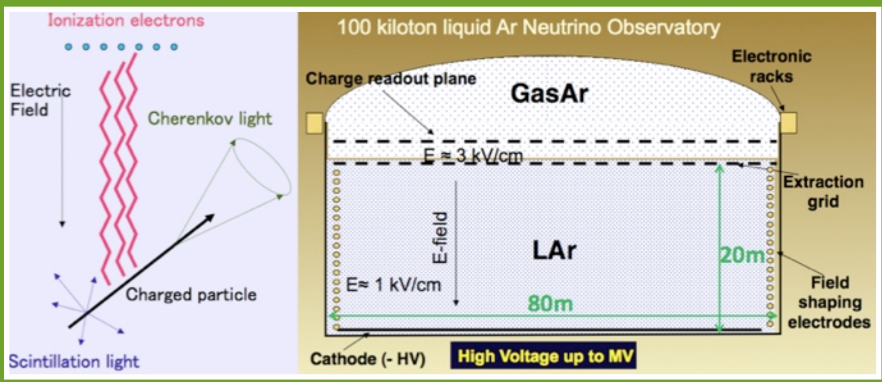
A liquid TPC is simply a TPC chamber filled with a noble element in liquid state. When a charged particle passes through, it emits scintillation light and Cherenkov light, and also produces ionization electrons along the path of the particle. All these are detected by GEM and photo sensors.



In a superconducting tunnel junction (STJ) detector, low energy photons can disrupt Cooper pairs, locally disturbing the superconducting state.



The multi pixel photon counter (MPPC) is a new silicon photomultiplier diode developed by Hamamatsu that amplifies photon signals and converts them to electrical signals.



The liquid argon time projection chamber (liquid Ar TPC) can reconstruct complete particle decay processes from time and three-dimensional position information.

Thus, a liquid detector can detect both Cherenkov light and other particles.

The liquid TPC would provide time information from the scintillation light, and three-dimensional position information from the ionization electrons and Cherenkov light. From these, physicists can reconstruct complete four-dimensional particle trajectory.

With these remarkable characteristics, liquid TPC can distinguish between electromagnetic showers originated from electrons and ones originated from photons. Both look identical to the current neutrino observatories because they are both a bunch of electrons, positrons, and photons. This means that physicists can distinguish between electron showers from electron neutrino events and photon showers from background neutrino events.

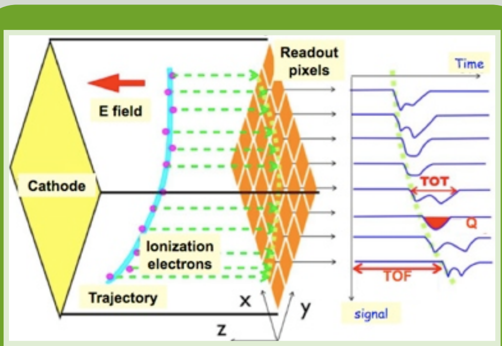
"We will be able to tell what flavor of neutrino has passed and reconstruct the exact trajectories of particles in the decay," says Haba. "Liquid TPC will bring a revolution in particle physics."

The liquid TPC is vigorously studied in medical research as well. As part of the next-generation positron emission tomography (PET) systems, it will provide much higher resolution images. PET is medical equipment that detects two gammas flying out in opposite directions as the result of electron positron annihilation near cancer cells. The current PET uses scintillator bars of 10 centimeters in length and a few centimeters square cross section, giving special resolution on the order of centimeters. With the liquid TPC, this will be brought down to the order of millimeters or better.

As promising as it looks, the challenges are daunting. One major difficulty will be producing the large volume of high quality liquid medium necessary for these applications. The liquid needs to be extremely pure so as not to disturb ionization electrons' paths. For neutrino experiment, it will require 100 kilotons of liquid argon, all of which needs to be cooled to keep the liquid state. In addition, they need to figure out how to apply one million volts to the container.

Catching up to the world

Application specific integrated circuits (ASIC) are customized IC chips to be used for a particular purpose. "It is not realistic to mass produce our ICs because we generally need only a small amount," says Haba. As ICs become smaller and higher performance, it has become difficult to produce ASICs without a well-established infrastructure. "Europe and the US have long put efforts on ASIC development, while Japan has put less focus on the matter."



The QPIX will be able to acquire time-of-flight information as well as the signal width.

The ASIC project aims to train ASIC developers beyond KEK at universities around Japan. The project has hosted ASIC programs to promote in-house ASICs. Now scientists at universities such as the University of Tokyo, Kyoto University, Saga University, and Tohoku University who have completed the program can fabricate detector readout systems on their own. At KEK as well, the team has developed ASICs for both the MPGD and liquid TPC.

Strengths of research and development community

The next-generation photo sensor project is the second largest project in DTP, and includes over 60 collaborators from various projects such as T2K, the International Linear Collider (ILC), and Belle. The project's main interest has been the multi pixel photon counter, MPPC, developed by Hamamatsu.

This year, the first large-scale MPPC application was completed at the T2K near detector. Altogether 63,500 MPPCs went into service just recently and are currently being tuned in preparation for the full-scale startup next month. The successful research and development of the MPPC owes much to the DTP photo sensor project at KEK and its collaborators.

The R&D activities proved to be useful experiences for collaborators from other projects. MPPC studies for ILC and Belle are ongoing. "The first generation of MPPCs has been completed," says Haba. "However, there are some disadvantages of MPPCs that need to be overcome for the next application. For example, you cannot make the pixel much larger than the order of 1-millimeter square as the noise grows steeply with the size." The team is currently exploring various options to overcome these problems.

Growing into the future

The DTP has grown to attract more than 260 collaborators. "Our primary goal to build a pipeline between projects has been accomplished," says Haba. "Also, the project provides a place where detector scientists can work on R&D of detector technologies not directly related to experiments at KEK."

Around a dozen DTP members meet every month to discuss their progress and to set the direction of the project. New technology under discussion is a pixel-readout ASIC called QPIX. QPIX is a multi-function pixel that measures total charge, time-of-flight, and signal width of particles. With QPIX, complete imaging of radiation will become possible. Currently around 10 people are working on the QPIX R&D.

Haba thinks that there is a room for improvement in terms of communication. "For wide variety of scientists at KEK, we'd like to improve the quality of seminars and offer places to discuss new technologies more casually." The DTP project welcomes new collaborators.

Related Link:
Detector Technology Project

CMB Group (Japanese)

Related Issue:
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