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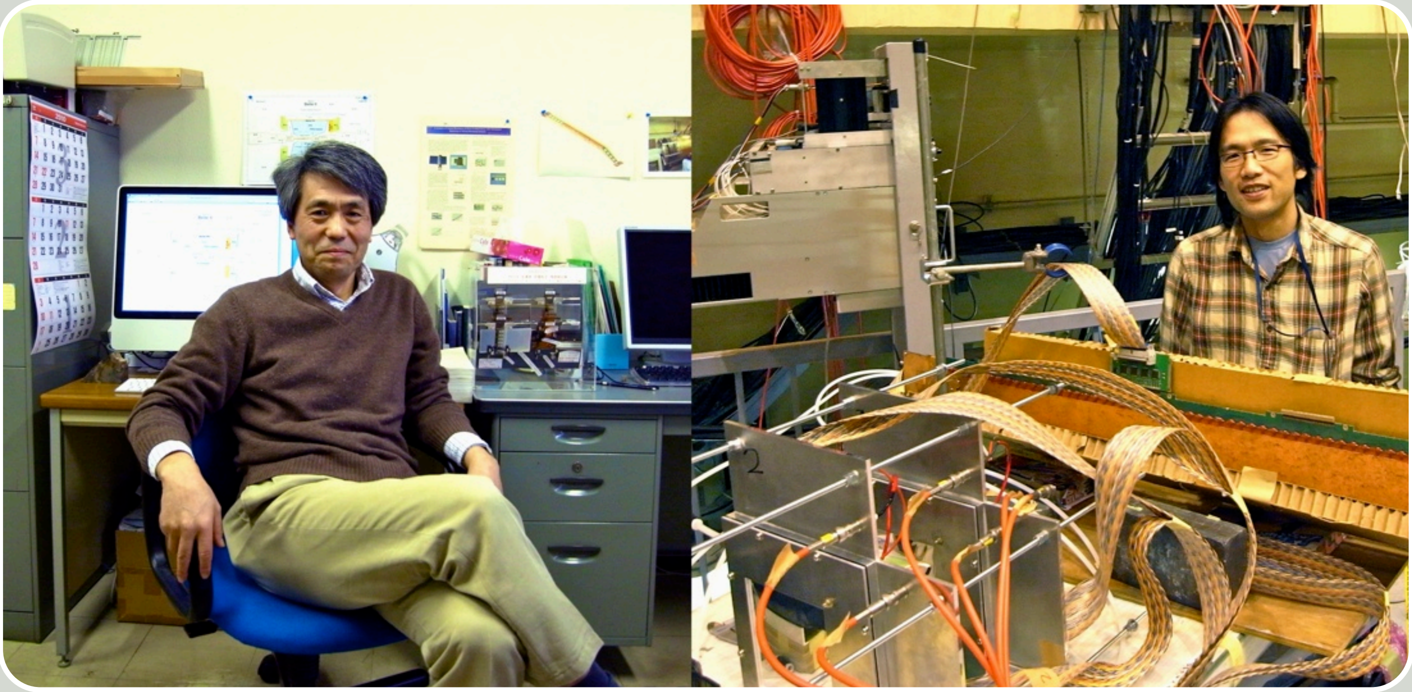
FEATURE STORY



Left: KEK’s senior engineer Takashi Kohriki in his office. Right: KEK physicist Dr. Shuji Tanaka during the beam test of his upgraded thin gap chamber (TGC) for the ATLAS upgrade.

ATLAS, Belle II, and *monozukuri*

[ATLAS Muon Chambers, ATLAS upgrade, Belle upgrade]

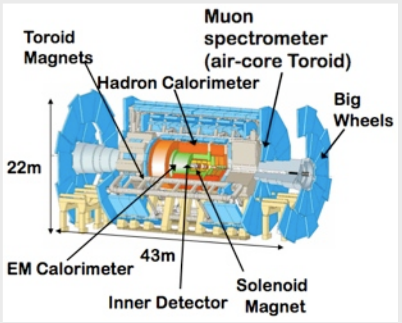
In the large worldwide community of accelerator science, there always are new projects for talented physicists and engineers to exercise their creativity. Read here a story of a physicist and an engineer at KEK who built components of the LHC's ATLAS detector from scratch, and are now making a difference at the Belle II experiment. Learn what it takes to develop state-of-the-art, unique devices.

KEK’s senior engineer, Takashi Kohriki, and physicist, Dr. Shuji Tanaka, are two very different people with very different backgrounds. It turns out, however, that they’ve taken quite similar paths in their careers. Both have worked on ATLAS since the very beginning, and both are now contributing to the Belle II upgrade. In separate interviews, they both use the word *monozukuri*—spirit of product making—synonymously with their challenges, processes, and goals.

Once a frequently heard philosophy that brought Japan rapid economic growth, *monozukuri* is now often replaced by the convenience of mass production automation. At KEK, the authenticity of the concept remains intact. “To create new technology requires a fundamental understanding of materials and functions,” says Kohriki. “Underlying everything is the attitude of *monozukuri*.”

ATLAS is one of the four major experiments at the Large Hadron Collider (LHC), the world's highest energy proton collider located at the European Organization for Nuclear Research (CERN). The purpose of the ATLAS experiment is twofold: to look for the last missing piece of the Standard Model, the Higgs particle, and to look for new physics beyond the Standard Model.

A proton is not an elementary particle, but instead a composite of elementary particles called quarks and gluons. It turns out that creating collisions between quarks and gluons is a good way to find new particles, providing a large cross sectional area for the strong interaction. Thus, physicists at the LHC smash protons together at the highest energy possible



Tanaka headed the team that developed and produced the muon endcap detector TGCs that are now installed on the six endcap muon disks called big wheels (BWs). Kohriki developed and produced the silicon strip modules for one of the inner detectors, the Semi-Conductor Tracker or SCT.

in order to find new particles. During the trial run late last year, the collision energy of protons reached 2.36 TeV, which means that the LHC is now the highest energy collider in the world. The collision energy will eventually be brought to 14 TeV.

Kohriki developed silicon strip barrel modules for the inner detectors, while Tanaka developed thin gap chambers for the outer muon detectors. With the successful start up of the LHC last November, both changed course, and began working on the upgrade project at KEK, the Belle II experiment.

Belle is an experiment within KEK's KEKB accelerator ring that is designed to collide electrons and positrons. Unlike protons, electrons and positrons are elementary particles. A collider of electrons and positrons often aims to study the detailed physics of known particles as well as to search for new physics, providing a clean environment. For this type of experiment, the important parameter is not energy, but luminosity—the rate of collisions. The KEKB has been setting luminosity world records since 2005.

The Belle experiment, in place since 1999, has successfully fulfilled its goal by finding a symmetry violation that partially explains why our universe contains matter instead of antimatter. By summer, KEKB will have closed down for good, but it will soon be reborn as the SuperKEKB, which aims for a 40 fold improvement in luminosity. The respective upgraded version of Belle is called Belle II, and technical design studies are currently underway.

Three to a hundred

The history of the ATLAS Japan group goes back to 1993 when there were only three Japanese physicists involved in the project. Tanaka, then just starting graduate school at Kobe University, was one of them. At that time, there were two high-energy hadron colliders being planned: one was the LHC, and the other was the Superconducting Super Collider (SSC) in the US, which aimed for a collision energy of 40 TeV.

For his master thesis, Tanaka started evaluating a prototype for a muon detector called a thin gap chamber (TGC). “A thin gap chamber, or TGC, is like an egg slicer of gold coated tungsten wires with a 1.8 millimeters spacing, connected to electrodes,” explains Tanaka. The slicer is enclosed in a thin chamber of just 1.4 millimeters in thickness. A mixture of carbon dioxide and n-pentane gas continually fills the chamber. “When a particle goes through a TGC, it hits and ionizes the gas molecules in the chamber, producing electrons and ions. The high voltage applied to the wires amplifies each individual electron to a cascade of tens of thousands or hundreds of thousands. This cascade can then be read out as an electrical signal.”

Among many candidates for the muon detector, the TGC was chosen because its basic performance met every requirement of the ATLAS experiment. First of all, because beam collisions at ATLAS would take place every 25 nanoseconds, the response time had to be very short. Second, the device needed to be fairly low cost. Third, the device needed to have the smallest possible dead region—the area where particles cannot be sensed. Lastly, the device needed to have a very short recovery time, to be able to recover the initial state quickly before the next particle hits. Tanaka's study showed that the TGC was just such a short response-time, inexpensive, short recovery-time, high efficiency (dead region less than 10 percent) sensor. The TGC was officially chosen to be the sensor for the ATLAS endcap muon trigger detectors in 1996.

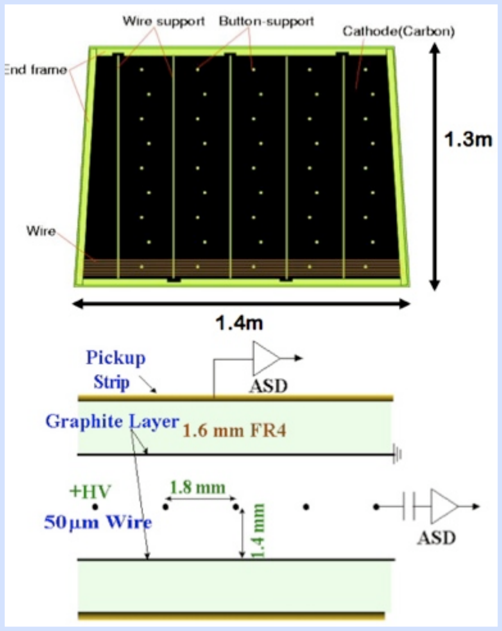
By then, the ATLAS Japan team had grown to dozens of members. With the termination of SSC project in 1994, most of the KEK scientists and engineers who had been working on the SSC joined ATLAS Japan. The collaboration eventually grew to include around a hundred members from 15 institutions.

Do-it-yourself production

The endcap muon detectors are six disks, each 25 meters in diameter, called big wheels (BWs). Once the design was chosen, the challenge was to actually produce the many TGCs, each 1.3 meters by 1.4 meters, required to cover the big wheels. Of the 3,600 TGCs required, Japan was responsible for producing 1,200. Each TGC needed about 1,000 tungsten wires in exactly equal spacing, and precise tensioning to prevent sags.

ATLAS Japan first tried contracting with private firms to construct the machineries for production. “It turned out to be not a good idea. Machines did not reach the level of performance necessary for our purpose,” recalls Tanaka. “Also, because we needed to adopt production line system, we had to make sure all machineries were reparable over night. This meant that we had to have good understandings of how machineries and production processes work, and allow no black box in process.”

Tanaka and his team designed and built the TGC production line which successfully produced 1,200 TGCs on schedule. (Upper row, left to right) Graphite spraying, framing, and wire winding on rotary. (Middle row left to right) Cleaning, making a singlet module, and sandwiching a paper honeycomb with two TGCs. (Lower row, left to right) making a doublet module, an image of singlet module, and an image of doublet module.



A TGC consists of about a thousand equally-spaced wires. When a particle passes though the chamber, it ionizes molecules inside the chamber. The resulting electrons are amplified by the high voltage applied on the wires of the TGC.

So he and the team members from Kobe University and KEK led by Prof. Hiroyuki Iwasaki of KEK basically built everything for the production line. Tanaka says that many specialists helped them along the way. He also visited Israel to learn about their production processes and materials.

People who know him well unanimously say Tanaka always succeeds in achieving the necessary technologies for experiments. His secret: local do-it-yourself centers. He knows them like his backyard. Tanaka and his colleague Dr. Koji Ishii (KEK) then at Kobe University returned to do-it-yourself centers frequently to browse around for just right piece of equipment. For them, a block print device is an adhesive applicator. The rotary parts of a revolving chair would turn a TGC board to make sure adhesive is applied uniformly. A pesticide applicator would clean TGC boards. And of course, a timer would turn it off in 20 minutes. Standard electrical switches would switch on and off the machines. A carbon box covers the rotary chains used to rotate the wire-winding, providing needed safety. The bonding of TGCs with paper honeycomb for strength would be done on a the flat surface of a granite table bought and polished at local shops, and drilled by the team to ensure a flatness of 100 micrometers precision.

The first TGC prototypes each took a month to produce. The wire bonding did not come out well the first time, and electrification did not work the second time. The team's test-and-modify approach, however, provided continual improvements. Between 2001 to 2005, they successfully produced 1,200 TGCs on schedule, helped by part-time workers and graduate students. The total expense was a tenth of that they would have needed if the production had been done by a private firm.

"The personal challenge for me was to understand *monozukuri*," says Tanaka. "This was the first time I had created machines to produce an experimental apparatus. To meet the demand of quality, schedule, and cost, we really had to have a clear idea of every step of the production process."

Seeking advanced technologies

Another important contribution of the ATLAS Japan team is in one of the innermost detector components, the Semi-Conductor Tracker, or SCT. The inner detector of ATLAS is composed of three components that track charged particles. From inner to outer, the components are the pixel detector, the semiconductor tracker, and the transition radiation tracker. Each of these three components has a cylindrical shape, and has both barrel and endcap components.

Kohriki played one of the leading roles in developing and producing the silicon strip barrel modules for the SCT. He started research and development for the hybrid board of the silicon strip detector board for SSC in 1992. By then, he had already worked on cryogenic technologies—in particular, bubble chambers—and later on one large-scale experiment TRISTAN's VENUS at KEK. He gained a wide range of expertise in central drift chamber, transition radiation detector, and other detector components. Kohriki says that these experiences certainly helped him later developing and constructing the SCT modules.

For the SCT, he opted to develop a smaller-sized, more sophisticated device rather than a large-sized device that used conventional technologies. To do this, he chose to study silicon strip detector technology. This was back when the SSC project was just starting.

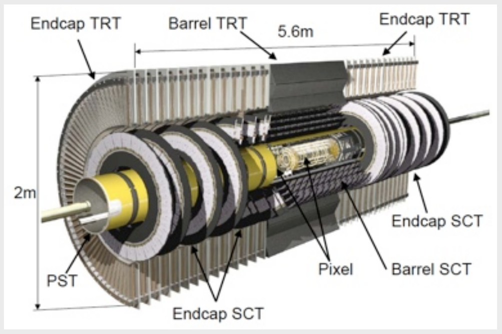
"High energy physics community has produced many innovations, from the world-wide-web to electronics technologies. That is because we try to understand every part of the process of creation," says Kohriki. He believes such *monozukuri* philosophy brought about the success of the SCT.

In particle experiments, it is also important that all materials are radiation-proof. It is also desirable to use the least amount of material mass and space as possible, so not to interfere with particles' paths. The board for the electronic readout that Kohriki engineered is called a flexible printed circuit boards. "The insulator of the flexible board is made of polyimide unlike ordinary green boards which are made of epoxy. This means that the flexible board has excellent resistance to radiation," explains Kohriki. All cables are built into one board, which has a thickness that is just half that of other printed circuit boards.

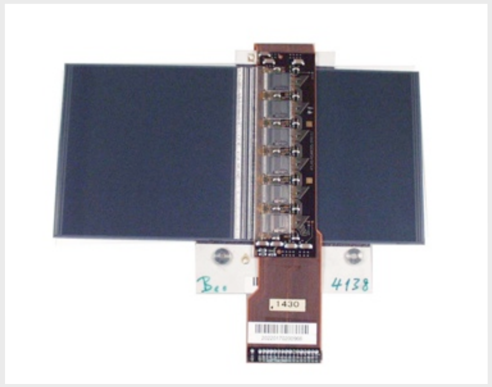
The thinnest and lightest flexible hybrid boards

The main competitor of the new flexible boards was a conventional ceramic circuit board based on beryllia—beryllium oxide. Beryllia is strong and has a good heat conductance, which is important to keep the system cool. Berillia, however, was harder to produce under Japanese regulation because of the toxic nature of the material, and also required soldering of wires and materials which would increase the mass of the device.

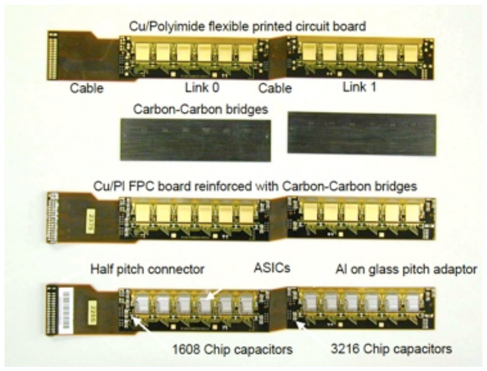
Kohriki utilized the flexible circuit technology that had been gathering attentions for some time. However, the chips on it need a strong back-plane to support them. For the strength and good heat conductance, he chose new material called carbon-carbon.



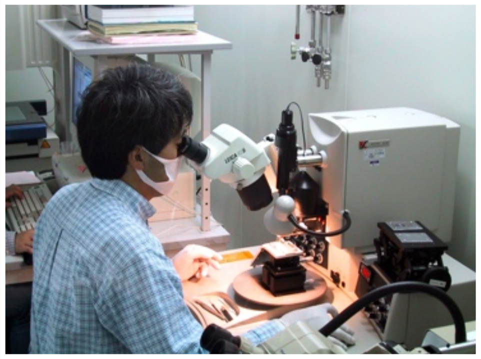
The ATLAS inner detector has three detector components. Together, these components work to track charged particles. Each has a barrel component and endcap components. Kohriki worked on the barrel SCT.



An image of a barrel SCT module.



Kohriki developed thin, light hybrid boards for the ATLAS barrel SCT modules. The Carbon-Carbon bridge is robust and has good thermal conductance in one direction.



Kohriki manually bond thousands of wires on the prototype flexible board.

The ATLAS barrel SCT is composed of four layers of cylinder with varying diameter. The image shows four-barrel assembly, installing the third layer.

This was produced by a Japanese company, Nippon Oil Corporation. The material was stiff and heat conductive in one direction, but flexible and only weakly conductive in another. “The carbon-carbon was a big hit,” says Kohriki.

The flexible polyimide circuit board was a four-layer of conductors and insulators. To make it as thin as possible, he first tried 8 micrometers electro copper plating for the conducting layers rather than using copper foil of 35 micrometers in thickness. The first prototype went well, but it went well for a wrong reason.

At this point, the development of the thinner and lighter flexible circuit board became challenging. Despite many attempts, Kohriki and Nippon Mektron, one of the leading companies near KEK, could not produce another successful prototype. The copper would simply come off when layers were stacked on top of it. Nippon Mektron gave up on the idea, but Kohriki could not. He pursued the flexible circuit boards persistently. “It turned out that the culprit was the heat—around 150 degrees Celsius—used in the lamination process. For plating, copper is sputtered on polyimide before using electro copper plating method. This sub-micrometer sputtered-layer could not withstand such high temperature. I tried copper foil which does not require sputtering, and was immediately successful,” says Kohriki.

After overcoming this difficulty, things became much easier. “The time was just right,” says Kohriki. “Then the copper foil technology was improving day by day, producing ever thinner and lighter foils. Additionally, we were able to make use of a new technology called copper-clad laminated sheet for flexible printed circuit board. Developed using Nippon Steel Chemical’s proprietary technology, the technology requires no adhesives.” Over just a few years, the thickness of available copper foil shrank from 35 micrometers to 12 micrometers. In addition, using the copper-clad laminated sheet removed the need for 30 micrometers of adhesive. As a result, he was able to develop a hybrid board with just 0.25 millimeters in thickness.

The resulting board was environmentally friendly, thin, light, and robust. More importantly, it was a well-functioning board with good heat conductance that required no wire soldering. At times, for the prototype, Kohriki would manually bond thousands of wires. “The eventual success is built on just such plain experience,” he says.

As do-it-yourself centers were to Tanaka, material and equipment exhibitions were to Kohriki. Kohriki attended at least one exhibition every month on his vacation in order to learn about new materials and garner new insights. He does not like waste. He thinks smart and economically.

Belle and ATLAS upgrades

The ATLAS experiment has just started. The LHC is striding towards its full capacity, running at 7 TeV this year, eventually increasing to 14 TeV.

“Detectors are harder to maintain than to produce,” says Tanaka. “We have yet to see if our detectors function as expected.” In addition to the maintenance, the teams have already started working on the research and development of the ATLAS upgrades. There are a handful of candidate detectors for the muon trigger system. Groups are now finalizing candidate designs, and the detector proposal is due later this year. Kohriki is working on even lighter and higher performance SCT materials making use of today’s advanced technology.

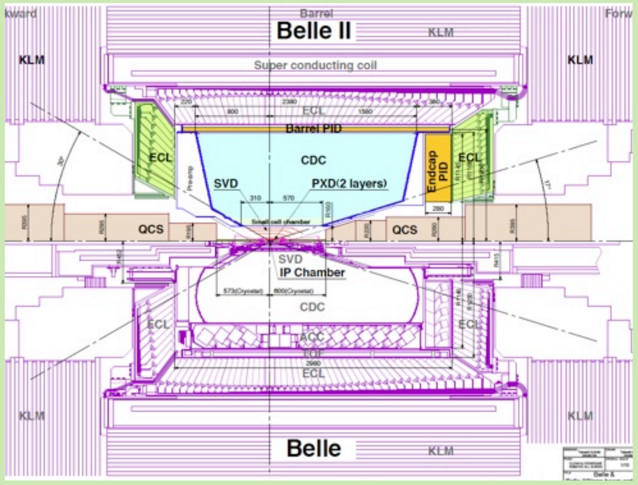
However, Tanaka and Kohriki are now both focusing on the Belle upgrade. Kohriki has already played a large part in the design of several components of the Belle II detector, including the structure of the inner detector, the central drift chamber, and the particle identification device. The challenge is to optimize the design to allow easy wiring of readout electronics and require a minimum amount of materials to maximize robustness.

Tanaka is working on the development and production of a new detector component, the pixel detector, which is to be installed at the very heart of Belle II. The device will sit in a very small space between the beam pipe and the silicon vertex detector. The small size of this space is currently the most challenging issue.

“There are many issues to be solved, but I think we are a capable collaboration and will be able to come up with right solution for each,” says Kohriki.

“ATLAS is a very large collaboration. Each of us was highly specialized, and didn’t know much about anything beyond what we did. Belle II is a collaboration of just 500, it’s nice and small,” says Tanaka. “On the other hand, Belle and Belle II have just the name in common. In actuality, they are very different entities, in a sense that Belle II is truly an international collaboration.”

Belle II collaborators are privileged to have both of these scientists in their collaboration. Tanaka’s energy to learn and create is an asset. As the leader of mechanical engineering group established in 2008 to support various experiments at J-PARC and KEK, Kohriki now endeavors to bring his *monozukuri* spirit to the Belle II collaboration.



The Belle design (below) and Belle II design (above). Tanaka works on the pixel detector, located near the beam pipe. Kohriki works on in structural designs for various components.

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