VISION 42

Associate Professor, Accelerator Laboratory,
High Energy Accelerator Research Organization (KEK) (Inter-University Research Institute Corporation)

Dr. **Takayuki Saeki**

Learning About Infinitesimally Small World of Elementary Particles is the Springboard for Learning About the Vast Expanses of the Universe

—— The International Linear Collider (ILC) is Expected to Unravel the Mysteries of Life and the Creation of the Universe

"Large accelerators are a fitting symbol for elementary particle physics. Without them, we would be unable to carry out experiments to explore the world of elementary particles, and without these experiments, we would be unable to make advancements in physics."

The above statement is a quote from a book published* by Dr. Yoichiro Nambu, who was awarded the Nobel Prize in Physics in 2008 along with Dr. Makoto Kobayashi and Dr. Toshihide Masukawa. Dr. Nambu goes on to say that in order to unravel the mysteries of the universe, "the amount of energy produced by accelerators must be increased if we are to discover new elementary particles and investigate unexplained interactions." In other words, once studies have been conducted into all of the possible reactions that an accelerator can trigger, the accelerator no longer has a useful role to play. For any further studies, a new accelerator that can produce much greater energy is necessary. By leveraging the capabilities of researchers from all over the world, the High Energy Accelerator Research Organization (known as "KEK") is leading an international project to build the new International Linear Collider (ILC). In this "Vison" section on the ILC, we discuss accelerators and elementary particles with Associate Professor Takayuki Saeki, who is at the forefront of the accelerator cavity technology that underpins the ILC.

*** Yoichiro Nambu, Quarks, Second Edition, 1998, Kodansha Bluebacks**

Profile of Associate Professor Takayuki Saeki

Born in 1966

Mar. 1990	B.S. in physics, Department of Applied Physics, Faculty of Science and Engineering, Waseda University
Apr. 1992	M.S. in physics, Department of Physics, Faculty of Science, University of Tokyo
Sep. 1996	Ph.D., Department of Physics, Faculty of Science, University of Tokyo
Sep. 1996	Research Associate, University of Tokyo, International Center for Particle Physics (ICEPP)
Mar. 2004	Research Associate, Accelerator Laboratory, High Energy Accelerator Research Organization (KEK)
Apr. 2008	Senior Assistant Professor, Accelerator Division VI, Accelerator Laboratory, High Energy Accelerator Research Organization (KEK)
Apr. 2015-Present	Associate Professor, Accelerator Division VI, Accelerator Laboratory, High Energy Accelerator Research Organization (KEK)

The Japanese scientific community is producing many of the world's leading researchers in the field of elementary particle physics

Physics can be roughly divided into two disciplines: theoretical physics and experimental physics. The former seeks to develop theories to explain known empirical facts and natural phenomena or to study unexplained physical phenomena based on mathematical hypotheses. Prominent Japanese scientists in this discipline include Yoshio Nishina, Hideki Yukawa, and Shinichiro Tomonaga.

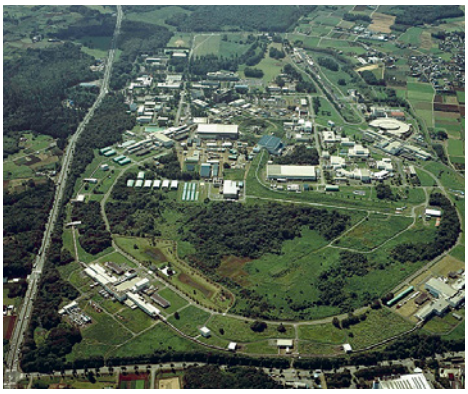
In experimental physics, however, experiments and observations are conducted in order to better understand natural or physical phenomena or to prove theories developed in theoretical physics. One of Japan's most renowned experimental physicists is Masatoshi Koshiba, who won the 2002 Nobel Prize in Physics for his detection of neutrinos.

Saeki: Professor Koshiba is a pioneer of Japanese experimental physics. Following his return to the University of Tokyo after studying in the United States, the professor led his own laboratory. The first three researchers to join his laboratory were Professors Shuji Orito, Sakue Yamada, and Yoji Totsuka.

I became a student of Professor Orito when I transferred from Waseda University to complete a master's degree at the University of Tokyo. So, I am essentially a second-generation pupil of Professor Koshiba.

I was only ever an average athlete during my childhood, but I loved to draw and ponder things—that's why I was sometimes called "child Buddha" [laughs]. I was good at science and math. At that time, science was all the rage. Rather than the class lectures and textbooks, though, I

KEK's History



Aerial view of the entire KEK Tsukuba Campus
(Source: KEK)

1971	High Energy Physics Research Organization established (Apr.)
1976	Proton accelerator (PS) succeeded in accelerating protons to 8 GeV (Mar.)
	PS succeeded in accelerating protons to 12 GeV (Dec.)
1982	Photon Factory (PF) succeeded in storing electron beam energy of 2.5 GeV (Mar.)
1986	Tristan Main Ring (MR) accelerated both electron and positron beams to 25.5 GeV (Nov.)
1998	B-factory succeeded in storing beams (Dec.)
	World's highest luminosity achieved, laying the groundwork for the Nobel-prize-winning theory by Dr. Kobayashi and Dr. Masukawa.
2009	J-PARC constructed jointly with Japan Atomic Energy Agency (Mar.)
	Long baseline neutrino oscillation (T2K) experiment commenced (Apr.)
2016	Beams successfully stored by the SuperKEKB (Feb.)

was more interested in specialist science publications. I studied them by myself and daydreamed about the Big Bang. I had already decided to become a researcher by going to university to study applied physics.

As we now know, the stars that we see in the night sky are actually hundreds of thousands of light years away, and what we see is actually images of them as they were at a point in the past as the light has to travel through the unimaginably vast universe before it reaches us. On hearing this, children in kindergarten or primary school tend to respond by asking: "But what's beyond the stars?" Grownups—and even great teachers—are unable to answer that question. Given this, I decided that I would have to figure this out for myself.

While I was studying for my doctorate from 1993 to 1995, I took part in a series of experiments in Canada where we used a balloon-borne instrument to observe cosmic radiation. For each experiment, the balloon was sent at the altitude of about 30 km into the air. After the observations had been completed, the rope was cut between the balloon and the instrument so that the observation instrument could be returned to the ground by means of a parachute.

Together with a retrieval team, the other researchers and I would then search the forests and fields for the landing instrument. If we couldn't use a car for the search, we would charter a military plane or trek by foot. My worst experience was when we had to search a marsh for the instrument. I learned the hard way that the job of an experimental physicist can be very tough—it can be physically demanding and require great perseverance [laughs]. The project leader back then was Professor Orito.

The Japanese physics community has produced many talented individuals who are leading the world in the study of elementary particles with the aim of unveiling the secrets of the universe. As a researcher, I too have benefited from the tutelage provided in this community.

KEK's accelerators have played a part in studies that have won the Nobel Prize for Physics

Elementary particles are the smallest component of a substance and they cannot be broken down any further. What we consider to be elementary particles has changed over time. Much of today's research into elementary particles is conducted in an effort to validate theoretic physicists' theories through a comparison with the results of experiments conducted by experimental physicists. If such research leads to a breakthrough, it could set us on the path to a new scientific civilization that is beyond conventional thinking.

Saeki: Research into the infinitesimally small world of elementary particles requires the use of special systems. Professor Koshiba, for example, studied neutrinos by observing them with a system called "Kamiokande", which is situated 1,000 m below the former Kamioka mine in Gifu Prefecture, Japan.

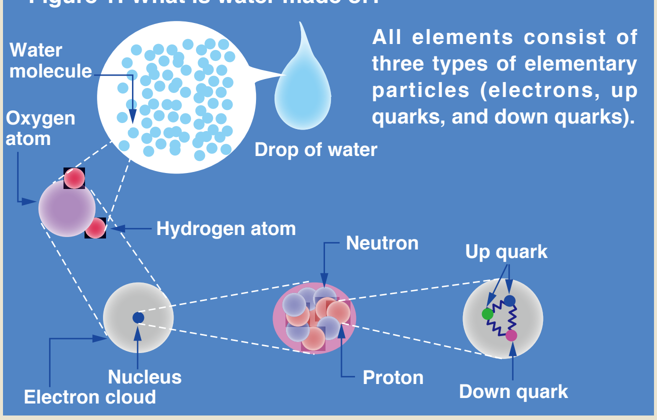
Sometime later, Professor Takaaki Kajita discovered evidence of neutrino oscillations based on the increased amount of observational data processed by "Super-Kamiokande", which has a capacity 15 times greater than that of "Kamiokande". This discovery was recognized with a Nobel Prize. In this experiment, a high intensity proton accelerator (J-PARC) operated by KEK was employed to artificially create and supply irradiate neutrino beams to "Super Kamiokande", which successfully observed the neutrino oscillations.

KEK's accelerator helped prove the existence of quarks as new elementary particles in line with the theories of Dr. Makoto Kobayashi and Dr. Toshihide Masukawa. Together with Professor Yoichiro Nambu, these theoretical professors won the Nobel Prize for Physics in 2008.

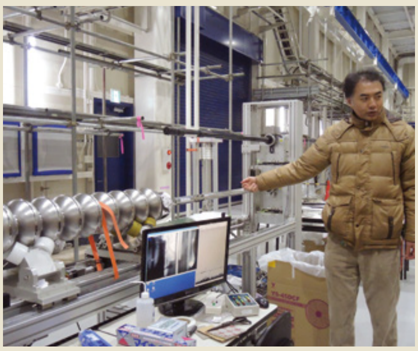
As a Japanese center of development for accelerator science, KEK provides opportunities for both Japanese and international researchers in related fields to conduct research using its various accelerators.

It may surprise some people to learn that applications of accelerator technologies can be found in our everyday lives. The microwave ovens found in most homes are based on the same principle as that of the high-frequency electromagnetic

Figure 1: What is water made of?



(Illustration created based on materials provided by KEK)



Superconducting accelerator cavity unit

An ideal vacuum is essential in accelerators. This photo shows an ULVAC ion pump.

field generators used in accelerators. Many other examples exist, including PET scanners for cancer screening, electron microscopes, sterilization units, X-ray diagnostic equipment, radiation therapy equipment, non-destructive testing equipment, and even obsolete appliances such as tube televisions.

The accelerator is an essential tool for elementary particle physics researchers.

Indispensable accelerators for elementary particle physics research

The microscope is a well-known tool for observing the world of the infinitely small. Theoretically speaking, though, it is impossible for a microscope to observe the molecular world at scale of 100 millionth of a centimeter—but an accelerator can.

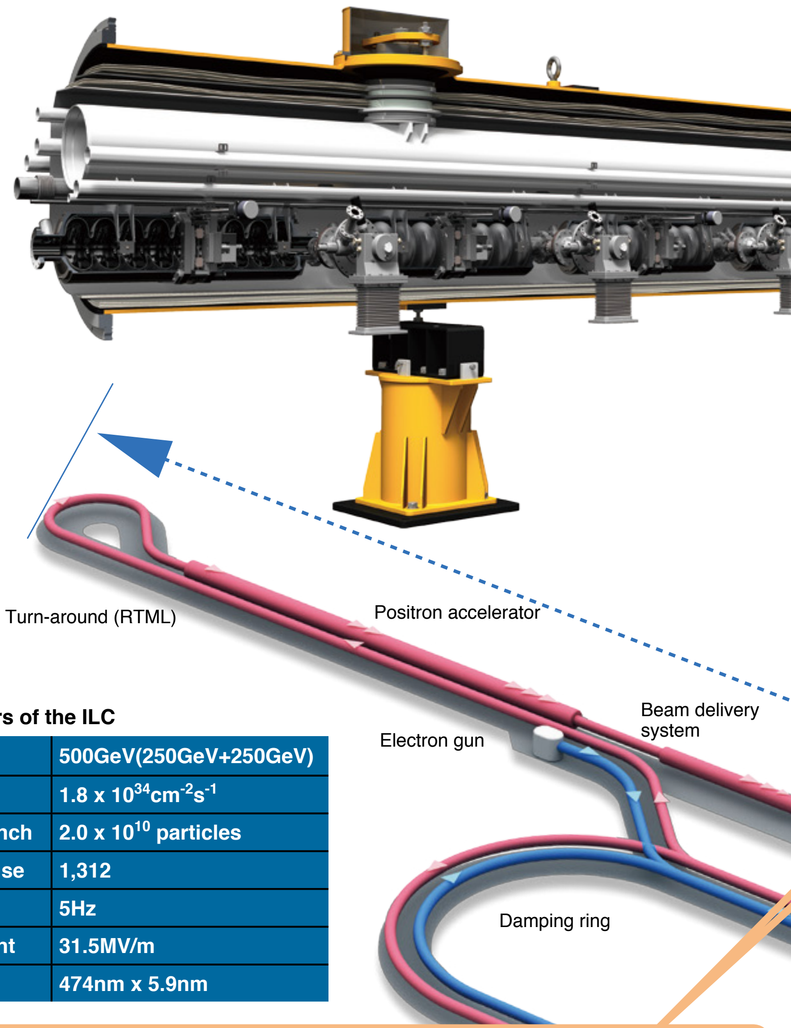
Saeki: The presence of electrons inside atoms was known as early as the late 19th century, and Ernest Rutherford attempted to visualize the internal structure of an atom in 1911. To do this, he collided alpha rays from radioactive elements at atoms to observe the degree of deflection or penetration. His experiments revealed that some negatively charged objects, which we now call electrons, were flying around some sort of a positively charged mass, which turned out to be the nucleus.

Mr. Rutherford’s collision of alpha rays at atoms marks the beginning of accelerators, and the principle has not changed since then. As a matter of fact, accelerators are also referred to as colliders. As it turns out, such collisions must be made by accelerating particles with much higher energy in order to study the inside of the atomic nucleus in detail.

Initially, the atom was believed to be made up of electrons, protons, and neutrons. However, following the development of technologies for space observation and experiments with accelerators, the existence of minuscule particles—called quarks—in protons and neutrons was predicted in 1964. Their existence was proven in 1969 in an experiment conducted in America using an accelerator.

In 1973, a theory proposed by Dr. Kobayashi and Dr. Masukawa predicted the existence of six types of quarks, including up and down ones. As mentioned earlier, the theory was validated using a KEK accelerator. Subsequently, new particles believed to be the root elements of matter were discovered, such as the electron-like lepton. Today, we can no longer declare with any certainty that we have a definite conclusion.

In fact, it has been revealed that the particles forming hydrogen and other familiar substances only account for 4%



Key beam parameters of the ILC

Beam energy	500GeV(250GeV+250GeV)
Luminosity	1.8 x 10^{34}cm^{-2}s^{-1}
No. of particles / bunch	2.0 x 10^{10} particles
No. of bunches / pulse	1,312
Pulse frequency	5Hz
Acceleration gradient	31.5MV/m
Collision beam size	474nm x 5.9nm

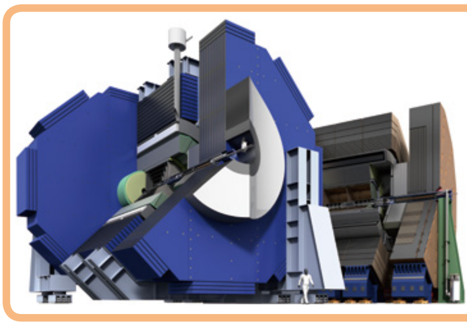


Figure 8: ILC detectors
(Image courtesy of KEK (c) Rey. Hori)
A collision detector placed at an interaction point (IP) between electron beams of 250 GeV and positron beams of 250 GeV captures the trajectory of particles involved in each interaction. The plan for a collision detector envisages the employment of ILD and SiD, and these two detectors will be used alternately in experiments.

of the entire universe. The mysterious dark matter and dark energy account for the remaining 23% and 73%, respectively. It is believed that research into dark matter and energy will help us to understand the beginning and evolution of the universe, so hopes for new accelerators are growing (Figures 2 and 3).

Electromagnetic, strong, weak, and gravitational: the four fundamental forces mediated by elementary particles

Elementary particles are believed to mediate the four fundamental forces behind all interactions involving matter on the Earth, in the solar system, in the universe, and on any natural world that lies beyond. These four forces of interaction are the electromagnetic, strong, weak, and gravitational forces.

Saeki: Electromagnetism, the most familiar of the fundamental forces, can be observed with lightening and magnets. This type of force is mediated by elementary particles called photons and it acts among electrically charged elementary particles. Both weak and strong forces act among protons and neutrons inside the atomic nucleus. The strong force is mediated among quarks to keep the protons and neutrons inside the atomic nucleus. According to conventional thinking, protons inside the nucleus would repel one another due to their positive charges, but this does not happen thanks to elementary particles called gluons, which bond protons together with their strong force (Figure 3).

The weak force, which is carried by elementary particles called Z (W) bosons, acts on quarks and leptons to trigger nucle-

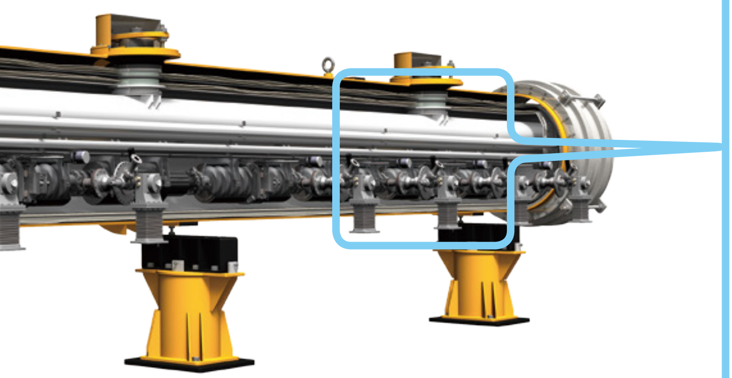


Figure 5: Cryomodule (Image courtesy of KEK (C) Rey. Hori)

Cryomodules are used in the KEK accelerator unit with a diameter of 1 m and a length of 12 m. Each module consists of a superconducting accelerator cavity unit or a superconducting quadrupole magnet, and a vacuum insulation vessel to provide thermal insulation for the helium piping. Two types of cryomodules are used: one houses nine superconducting acceleration cavity units, while the other houses eight superconducting acceleration cavity units and one superconducting quadrupole magnet. In the ILC, 1,680 cryomodules are installed in a straight tunnel underground.

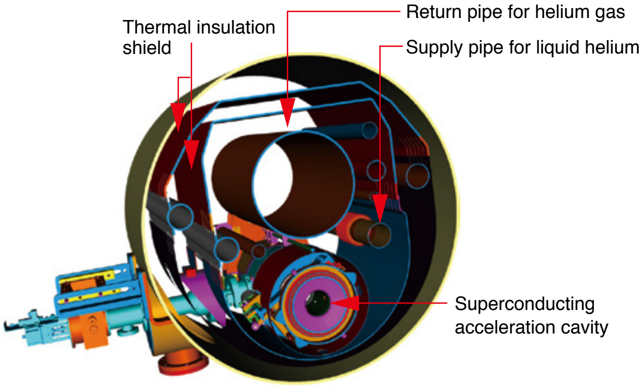


Figure 7: Cross section of cryomodule
(Image courtesy of E-XFEL/DESY)

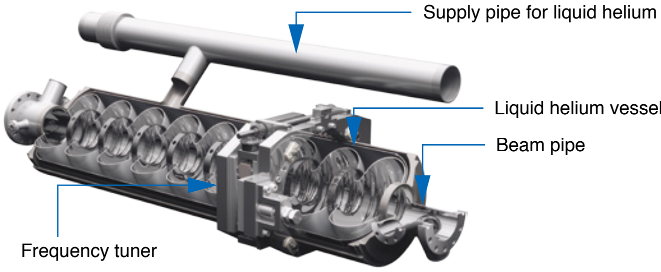


Figure 6: Superconducting acceleration cavity unit
(Image courtesy of KEK (C) Rey. Hori)

A superconducting acceleration cavity unit is a system that integrates a 9-cell cavity with an acceleration gradient of 31.5 MV/m, a helium jacket around the cavity that can be filled with liquid helium, and a frequency tuning mechanism to maintain and control resonance in the cavity. A cavity made using niobium (Nb) becomes superconductive without electric resistance when it is cooled to an absolute temperature of 2 K (or -271℃) using liquid helium. It can generate a high accelerating electric field with a small amount of RF power.

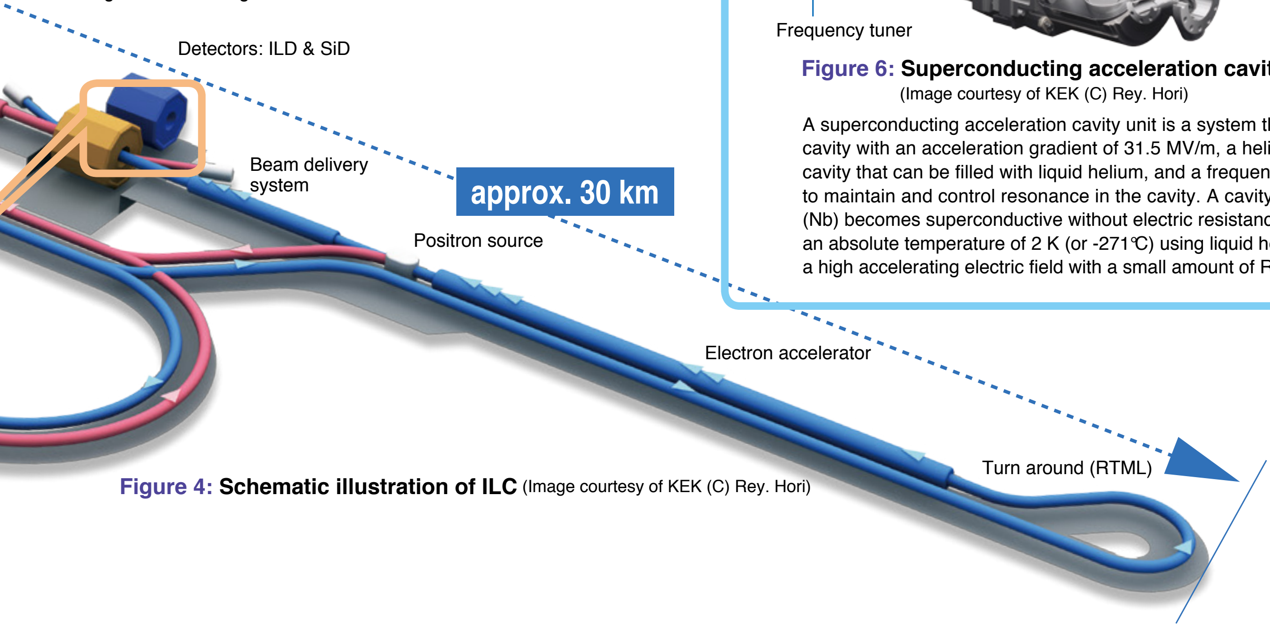


Figure 4: Schematic illustration of ILC (Image courtesy of KEK (C) Rey. Hori)

ar decay. It is owing to this force that our Sun is able to continue burning.

The gravitational force remains a complete mystery—nothing is known about it. This feeble force of attraction does not involve any positive and negative charges or any corresponding force of repulsion. It is so feeble that static electricity that has been built up on a celluloid sheet can lift up our hair. This phenomenon demonstrates that the force of attraction exerted on hair by a celluloid sheet charged with static electricity is stronger than the gravitational force exerted by the vast mass of the earth.

In 1964, the existence of the Higgs boson was predicted to be an elementary particle that is related to gravitational force (and mass). It took a state-of-the-art accelerator to finally confirm its existence in 2012. It is considered to be responsible for

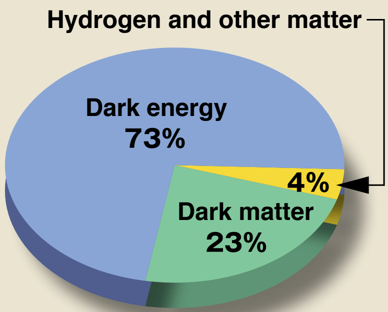


Figure 2:
Composition of the universe
(Image courtesy of KEK)

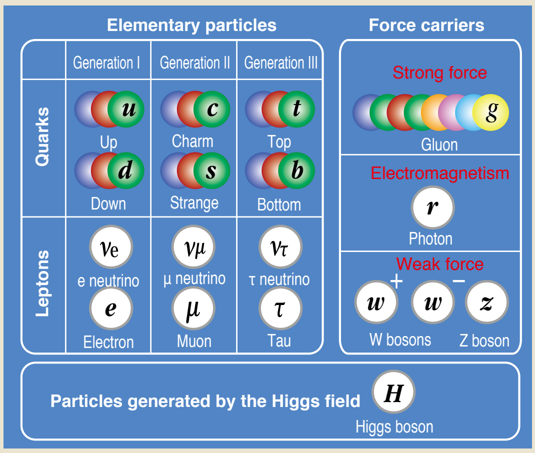


Figure 3: Elementary particles that shape the universe
(Image courtesy of KEK)

Figure 9: With a circumference of about 27 km, the Large Hadron Collider is the world's largest accelerator. It is operated by CERN in Geneva, Switzerland. (In comparison, the distance travelled by the Yamanote railway line that encircles central Tokyo is 34.5 km. Lake Geneva and Geneva Airport can be seen in the background of the photo behind the circular accelerator) © 2001–2017 CERN

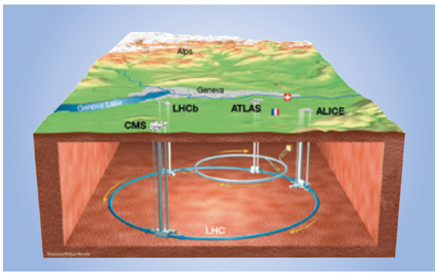
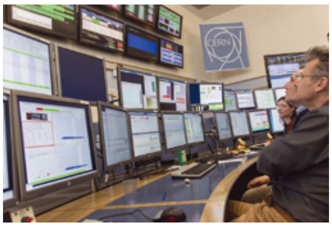


Illustration of the underground installation of the LHC © 2014–2017 CERN

ATLAS Experiment © 2016CERN



LHC control room
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Inside the LHC tunnel
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the mechanism that causes the respective elementary particles to acquire a specific mass.

ILC: a linear collider that could help unravel the Big Bang

An accelerator is used to observe phenomena at the interaction points where particles are brought into collision. This experimental system may not seem to have anything to do with understanding the universe, but observing phenomena at one infinitesimally small point provides clues to unravelling the mysteries of the beginning of the universe and the origins of life. In other words, we can learn about the vast expanses of the universe by studying the behavior of infinitesimally small elementary particles.

In 2008, construction of the Large Hadron Collider (LHC), the world's most powerful accelerator, was completed by the European Organization for Nuclear Research (CERN). This vast circular accelerator has a circumference of around 27 km, which is almost the same distance as the length of the Yamanote railway line that encircles central Tokyo. It was this CERN accelerator that successfully observed the Higgs boson (Figure 9).

Saeki: The LHC accelerates two proton beams travelling in opposite directions over the course of a number of laps before particles carrying great energy eventually collide.

Importantly, each proton is a combination of three quarks. Basically, a proton is a mixture of particles. Conducting an analysis of how the behavior of particles changes as a result of their collision is complex and prone to errors. One disadvantage is that particles accelerated close to the speed of light by a circular accelerator lose a huge amount of energy by emitting light and discharging electricity.

To overcome these challenges, pure electrons and positrons (the antimatter of electrons) need to be brought into collision with much greater energy. This is how the proposal for the development of a linear accelerator ILC came about (Figures 4 and 8).

Saeki: In a sense, the ILC is a huge experimental system that recreates the Big Bang inside it with the aim of unravelling the mysteries of the universe. Unlike circular models that can accelerate particles multiple times as they travel along their rings, a linear accelerator has only one chance to bring particles into collision. The probability of a collision must be increased as much as possible to make up for this disadvantage. Consequently, collections of electrons and positrons must be focused into dense beams. This function is fulfilled by the dumping ring and the final focus system shown in Figure 4.

The groundbreaking mechanism of the ILC

The ILC is an international project that is intended to allow researchers from Asia, North and South America, and Europe to collaborate in elementary particle research. Japan is the most promising candidate for securing the project, and the mountainous areas of Kyushu and Tohoku have been named as candidate sites for the construction of the accelerator.

With the Higgs boson having been discovered at the LHC in 2012, there are high expectations that the improved functionality of the ILC will help us take the next step toward a new research theme.

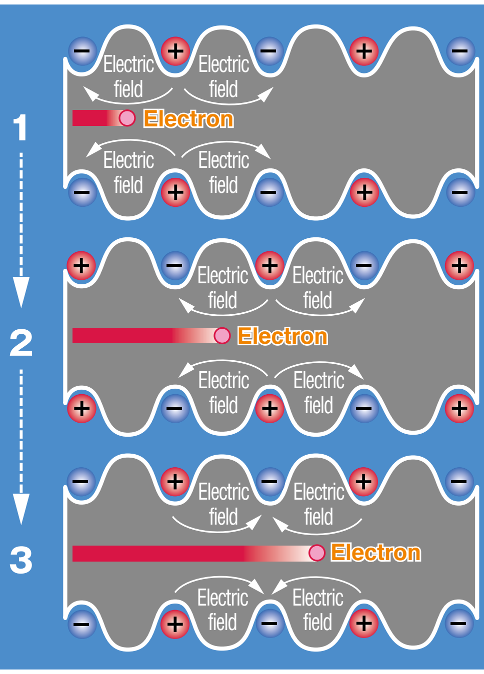
Saeki: Starting in 1996, I spent six years carrying out research at CERN. The tunnel, where the LHC is today, used to house the

Figure 10: The driving force behind linear acceleration

As shown in the figure, the ILC accelerates electrons with alternating electric fields (i.e., positive and negative).

The exceptional designed energy efficiency for the high-frequency power in the L-band (1.3 GHz) is produced thanks to superconductivity, with a temperature maintained at -271°C (2K) by cooling the superconducting acceleration cavity from the outside with liquid helium.

(Illustration created based on materials provided by KEK)



Large Electron–Positron (LEP) collider. In those days, the accelerator was use to conduct experiments where electrons and positrons were brought into collision. I studied the pair production of elementary particles called W bosons using the LEP collider. Later, CERN converted the LEP collider into the LHC. Following my return to Japan in about 2003, I began working in earnest to turn the ILC project into reality. Even if the newly completed LHC discovered the Higgs boson, questions regarding dark matter and energy would not be completely answered—that is why I believed that an even more upgraded accelerator would certainly be necessary.

To raise the energy of electrons (or positrons) by accelerating them in multiple stages, the ILC consumes vast amounts of electric power. Furthermore, in order to efficiently harness a strong current, superconducting technology is employed in the cavity units that accelerate the particles. These superconducting cavity units are cooled with liquid helium. Thermal insulation is ensured through the use of surrounding cryomodules that resemble giant thermos flasks. This is my specialist area (Figures 5–7).

Superconducting acceleration cavity units are made of niobium, a superconducting rare metal. Other outstanding superconducting materials called high-temperature superconductors do exist at present, but most of these ceramic-like (or earthenware-like) materials cannot form the complex, curved caterpillar-shape used for these cavity units. That is why we use niobium as a superconducting pure metal. Niobium is certainly an expensive rare metal, but a significant cost reduction is expected if a film of niobium can be formed on the inner surface of a copper mold. Similarly, applying a thin film of a high-temperature superconductor on the inner surface of the cavity would resolve the issue of workability and deliver excellent superconducting performance. In other words, it may be possible for a superconducting accelerator to operate at the temperature of liquid nitrogen in the future. Such an advanced thin film technology would help to reduce the size of superconducting accelerators dramatically and slash production costs. We hope to develop such a technology through joint research between ULVAC and KEK (see the column below).

The acceleration of electrons (or positrons) by an alternating (i.e., not one way) electromagnetic field in the ILC is carried out based on the mechanism shown in Figure 10. Technically, it is much easier to handle direct current, but accelerating to a high speed using this would require a correspondingly high voltage, which in turn would cause internal sparks (basically lightening) and destroy the accelerator.

As shown in the figure, the application of alternating current can accelerate particles without raising the voltage, thereby avoiding the generation of sparks.

Significance and mission of the ILC project implemented by Japan as a leading scientific nation

Children and adults alike wonder about how the universe came into being and what lies beyond the universe? Research conducted using the ILC attempts to answer genuine questions such as these. With a smile on his face, Associate Professor Saeki says with absolute certainty that the newly installed ILC contributes something more than just immediate and direct gains.

Saeki: I have no doubt that, over the next few years, the ILC will make an immense contribution toward the advancement of our scientific civilization. I am very confident about its potential.

Dr. Saeki stood next to a cryomodule

Elementary particle physics researchers around the world openly share their research findings across borders. Through friendly competition, they strive to unravel the mysteries of the beginning of the universe and the origins of life through tireless research.

The implementation of the ILC project is extremely costly. Given this, the project cannot be realized without the full understanding and support of the Japanese public and government.

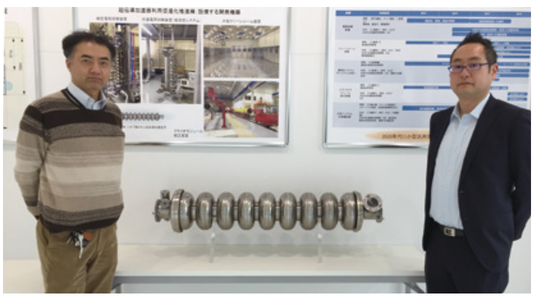
Even the groundbreaking findings achieved by the ILC do not mark a definitive end to our quest for knowledge. Take dark matter and energy, for example. The more we know in science, the more unexplained fields of research emerge. Indeed, as soon as we reach one destination, it becomes a new starting point. Sooner or later, the ILC will need to be replaced by another accelerator.

It is no exaggeration to say that I am devoting all of my energy to implementing the ILC plan. I believe that the ILC will be of benefit to the scientific researchers of the future, including those who are still in school today. It will certainly lay the foundations for scientific advancement in Japan.

Tomohiro Nagata

Manager, Advanced Material Research Section, Future Technology Research Laboratory, ULVAC, Inc.

A powerful tag-team for the advancement of science



Nagata and Dr. Saeki (left) stood in front of a superconducting acceleration cavity unit

During my temporary assignment to KEK in fiscal 2012, I had the opportunity to work with Dr. Takayuki Saeki. Even today, I still draw on the time we spent together assembling measuring instruments and engaging in deep discussions late into the night.

Building on this experience and my human network from those days, my current group is engaged in joint or collaborative research with KEK based on three themes. One is the joint research that we began in fiscal 2016 with Dr. Saeki regarding an accelerator component called the superconducting thin-film acceleration cavity. This research is aimed at validating and commercializing a theory predicting that accelerator performance can be significantly enhanced through the use of thin-film superconductors. In this research, KEK is able to leverage its knowledge of superconductivity and accelerators, while ULVAC contributes through its strong background in thin-film technologies.

Lately, the application of thin-film technologies has begun to attract considerable attention. We consider this joint research with Dr. Saeki to present a great opportunity for us to demonstrate ULVAC's technical sophistication. At this stage, we are carrying out a basic verification, after which we will forge ahead toward commercialization by overcoming the challenges we face one by one.