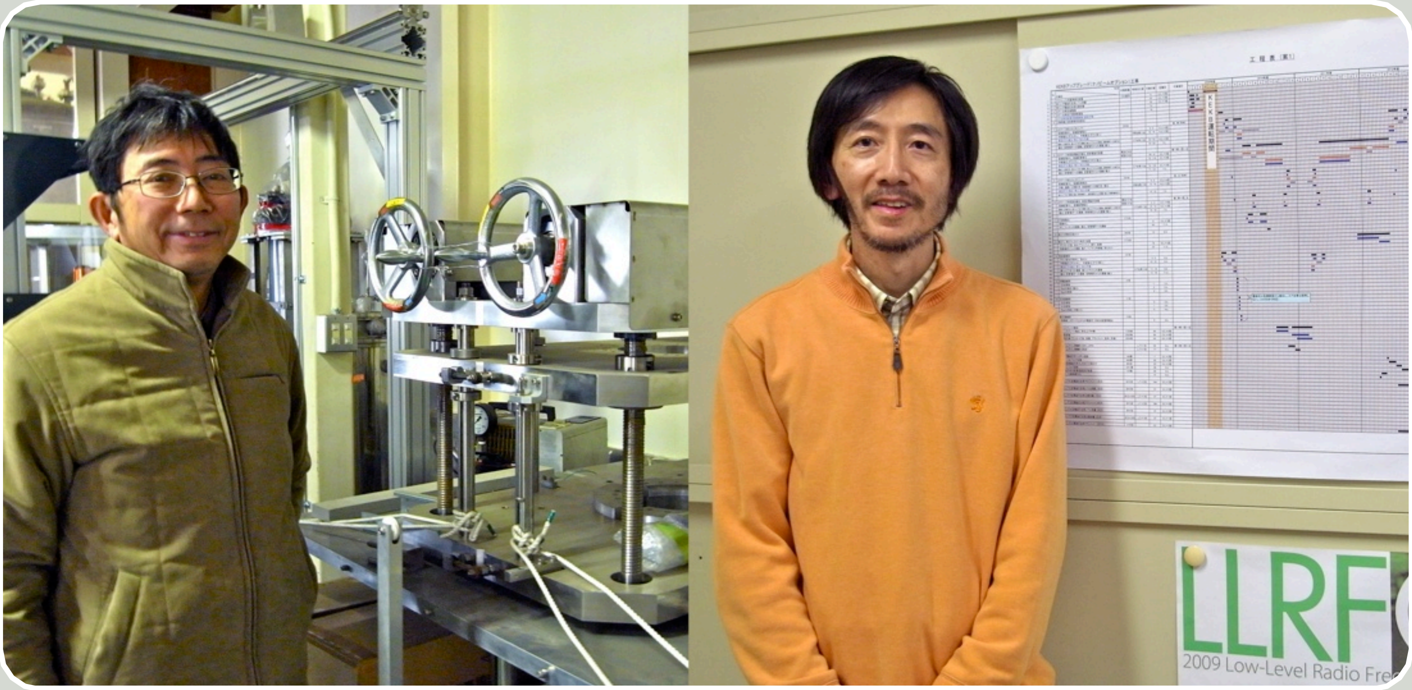


Left: Prof. Kenji Hosoyama of KEK and his team developed and built the successful KEKB crab cavities. Right: Prof. Kazunori Akai of KEK developed the baseline design work for B Factory crab cavity when he was on sabbatical at Cornell University.

KEKB crab cavity may help LHC upgrade

[KEKB, Crab Cavity, LHC Upgrade]

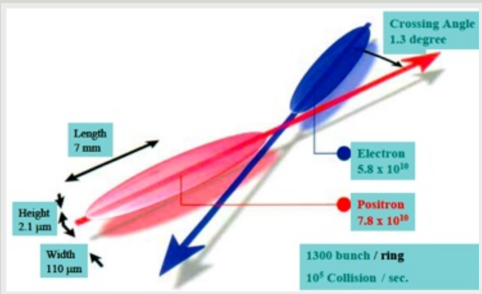
In 2009, the KEKB accelerator set a new world luminosity record with the help of a newly installed device called a crab cavity, and the integrated luminosity of KEKB reached 1,000 inverse femtobarn. This is the world's first successful installment of a crab cavity. KEK scientists' expertise in this new technology will help in an upgrade of the Large Hadron Collider at CERN. Here is why.

On Thursday February 18, prominent particle physicists and Ministry staffs gathered in one room at KEK to celebrate the great achievement of KEKB: the integrated luminosity of 1,000 inverse femtobarn. Nobel laureate and Professor Emeritus of KEK, Makoto Kobayashi, said of the particle collider that experimentally confirmed his Nobel prize winning theory: "KEKB has brought out its best and beyond."

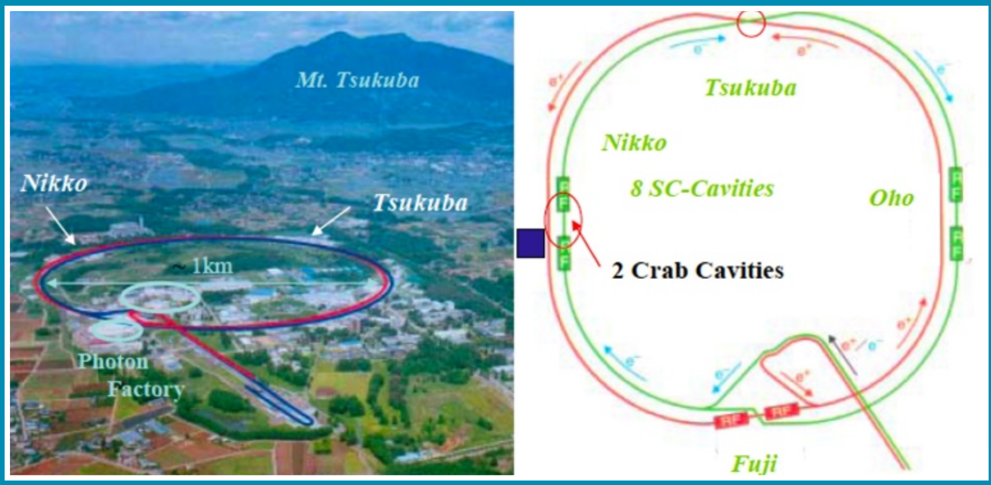
An inverse femtobarn is a measure of the rate of particle collisions per area. When KEKB began operation in 1999, the target integrated luminosity was 500 inverse femtobarn. Indeed, Kobayashi was surprised by the speed at which upgrades to KEKB were improving the luminosity. In 2003, then a head of the Institute of Nuclear and Particle Science, he reset the target integrated luminosity at 1,000. "To achieve the world record in luminosity is not a simple task, but is instead the result of hard work, brilliant ideas, and good luck," says KEK's Director General Prof. Atsuto Suzuki. "Everyone who has contributed in to achieving this milestone is to be celebrated."

One important milestone was the successful installment of a crab cavity in each ring of KEKB. KEKB is well known for continually setting and breaking the instantaneous peak luminosity world record since 2001. It has achieved a peak luminosity of 2.11 x 10^{34} inverse square centimeters per second (21.1 inverse nanobarn per second), over twice as much as the original design peak luminosity.

The installation of crab cavities in KEKB gave the final and vital kick to produce this luminosity record.



KEKB's beams of electrons and positrons make a finite angle when they cross.



Two superconducting crab cavities were installed in the KEKB accelerator ring at KEK.

A particle accelerator drives particle beams that consist of a series of particle bunches. At KEKB, there are two separate beams, an electron beam and a positron beam. The beams cross at a horizontal angle in the center of the Belle detector. The bunches are ribbon shaped, around 5 millimeters long, 100 micrometers wide and a micrometer thick. Because the bunches are so narrow, not all region interacts when they collide. To increase the number of particle collision events, accelerator scientist Prof. Robert Palmer came up with a concept called a crab crossing more than thirty years ago. A device called crab cavity gives a tiny sideways kick to each particle bunch so that bunches collide head on, rather than crossing in an angle.

“The idea was already there, but the technology to make it work is very difficult,” says Prof. Andrew Hutton, the head of the accelerator division at Jefferson Laboratory, who chaired the KEKB review committee. Because of the thinness of the two bunches, the slightest error in positioning can cause them to slip right past each other, without interacting at all. It is the team at KEK that took the complex design behind the crab cavity and made it work.

The crab cavity at KEKB is currently the only successful crab cavity in the world, and its success has encouraged particle scientists around the world. Now, CERN’s Large Hadron Collider (LHC) scientists are looking into installing crab cavities in the LHC upgrade.

LHC upgrade

The LHC is a ring, 27 kilometers in circumference, and 100 meters underground. The LHC creates a pair of proton beams, travelling in opposite directions, and smashes the beams together. It smashes protons at four major experimental sites—ATLAS, ALICE, CMS, and LHCb—to look for new elementary particles and evidence for new physics. The LHC successfully completed a test run late last year at a beam energy of 1.18 TeV, producing a wealth of data. This made it officially the world’s most powerful particle accelerator. This year, the LHC is starting with actual physics experiments at an energy of 3.5 TeV, half the designed energy of 7 TeV.

Because of the intense radiation from the particle collisions, detector hardware corrodes very quickly. The hardware damage would only increase the time the hardware takes to process a signal without an error. In order to keep up the good performance, one thing scientists can do is to increase the rate of particle collisions per area. To investigate the feasibility of using crab cavities at the LHC, the LHC crab cavity team at CERN is joined by the accelerator scientist who developed the crab cavity at KEKB, Prof. Kenji Hosoyama of KEK.

A cavity that contains electromagnetic waves inside

Hosoyama and his team have worked on various superconducting technologies, including both superconducting magnets and superconducting cavities. When he began working as an accelerator scientist over 30 years ago, superconducting cavities were just emerging. He illustrates the miracle of superconducting cavities using an example from his childhood.

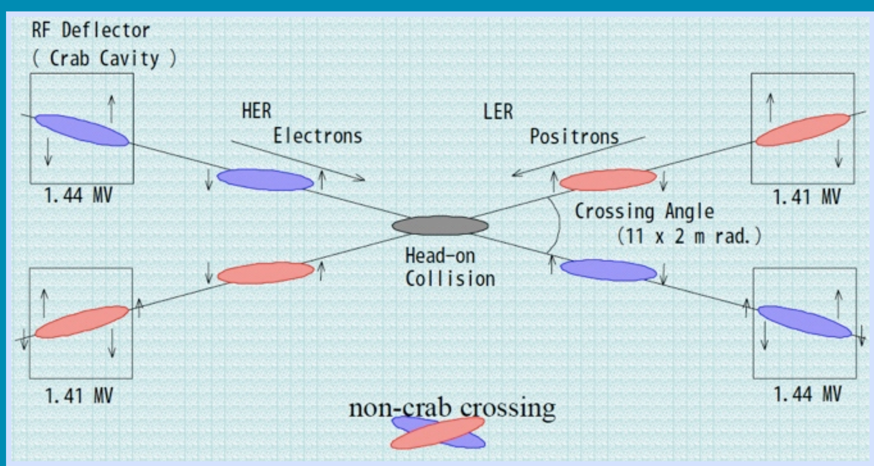
Hosoyama begins by asking us to think about light. What could you do to contain it in one place? Perhaps you could build a box with mirror walls, in which the light would bounce around forever. As a child this was his thought experiment. Unfortunately, this setup doesn't actually work. Mirrors can reflect light at very high efficiency, but they are not perfect. Each time a ray of light hits a mirror, a tiny fraction of the light is absorbed. A ray of light in Hosoyama's box would be reflected billions of times in a single second, losing just a bit of its brightness each time. This means that the light in the box would dim into nothing in an instant.

Hosoyama carried his disappointment until the day he learned about superconducting cavities. In a superconducting material, electrical current can flow without any resistance. This characteristic allows for extraordinarily perfect reflection of electromagnetic waves (light) at the surface of a superconducting material.

The quality of a superconducting cavity is measured by the number of cycles (one cycle is a singe back-and-forth reflection) for which an electromagnetic wave can be contained inside. This is called Q value. Using a normal conducting mirror, microwaves can be contained for about 104 cycles before the light is reduced to half it's original brightness. On the other hand, using a superconducting mirror, the light can be contained for 109 cycles before it gets reduced to half. This means that, if one were to use superconducting mirrors, the microwave would last for an order of seconds, a hundred thousand times longer than for normal conducting mirrors. It also means a hundred thousands times less heat generated, and a hundred thousands times less power required to generate the electromagnetic waves that drive particles (though it costs power to cool the cavities to the superconducting temperature).

Designing a crab cavity

According to Professor Hutton, “Akai-san is the father [of the KEKB crab cavity], and Hosoyama-san is the mother.” Prof. Kazunori Akai of KEK,



Crab cavities kick beam bunches sideway so that the bunches would collide head on.

then on sabbatical at Cornell University, did the baseline design work for the B Factory crab cavity in 1993. Cornell University's proposal for the CESR-B Factory required crab cavities. The design was also applicable to KEKB.

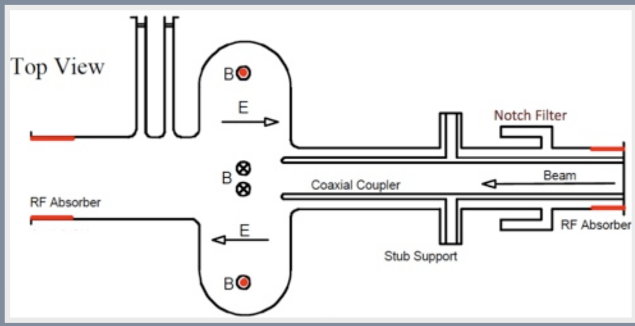
Inside a crab cavity, electric fields are produced parallel to the direction of beam on the left hand side of the beamline, and antiparallel on the other side. The two opposing electric fields create a loop of magnetic field on each side of the cavity so that a bunch passing through the middle would receive appropriate sideway kicks by just the right amount. This two-loop mode is called crab mode.

The difficulty with this scheme is that the high current beam can also excite tens of unwanted modes inside the cavity. The primary mode of concern is one large loop of magnetic field around the beam's path, called an accelerating mode. The secondary mode of concern is a two-loop magnetic field 90 degrees rotated from the fields of crab mode with respect to the beam axis. This mode is called vertical polarization mode. (The crab mode is thus a horizontal polarization mode.)

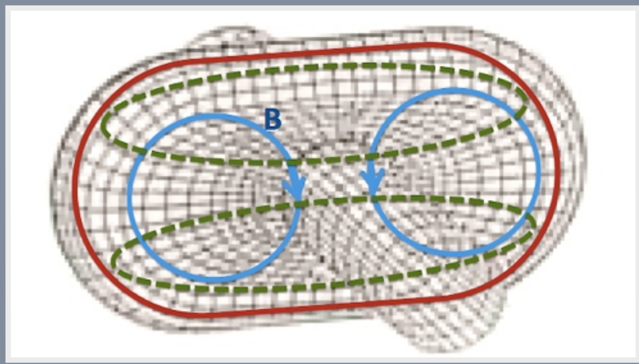
Akai worked to design a crab cavity that eliminates these unwanted modes. After a few months of hard thinking, his final cavity design came to be a squashed, oval cell that continues to a beam duct that contains another coaxial beampipe inside. The ingenuity of this design is that it eliminates unwanted modes efficiently while maintaining the high Q value for the crab mode.

The electric field created between the coaxial beampipe and the cavity wall couples with unwanted modes in the cell, and takes them away. When electric field is applied in radial direction, the electric mode (called monopole mode) couples strongly with the accelerating mode, and takes it away from the inside cell. On the other hand, when electric fields are applied perpendicular to the axis of beampipe in one direction, the electric mode (called dipole mode) couples strongly with the polarization modes in the cell. The oval shape of the cell distinguishes the vertical and horizontal polarization modes. In case of the vertical polarization mode, the magnetic field loops contract in the vertical direction of the cell. The contracted magnetic field loops have higher excitation frequency than the circular loops of the crab cavity mode. Akai calculated the diameter of the coaxial beampipe so as to make the cutoff frequency for the coupling sit between the frequencies of the two polarization modes. In effect, this means that the dipole mode of the coaxial beampipe couples only to the vertical polarization mode, but not to the crab (horizontal polarization) mode.

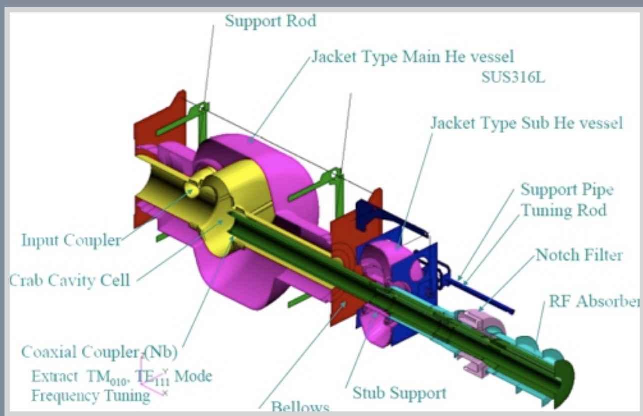
"However, a slight misalignment of the coaxial beampipe can create an electric monopole that can couple to the crab mode, which takes a portion of the crab mode away from the inside cell," says Akai. So he also developed a filter called notch filter. A narrow notch of depth that's one-forth of the crab mode wavelength goes around the beampipe to send the crab mode back to the cell if it ever arrives.



The conceptual design of KEKB's crab cavity.



The oval-shaped crab cavity creates two-loop magnetic field (blue) inside to kick bunches sideway. It is called crab mode. Unwanted modes, accelerating mode (red) and vertical polarization mode (green), are also excited.



Akai also calculated various other parameters such as maximum electric and magnetic field strengths to determine the optimal shape for the crab cavity. He then took the completed design and actually built a miniature model cavity, cooled it to superconducting temperature, and measured the fields. "Two crucial requirements need be satisfied for a B Factory crab cavity. First is the sufficiently strong field of the crab mode, and second is the beam stability under the high current beam environment that B Factory generally requires," explains Akai. His model crab cavity successfully demonstrated every feature required by B Factory experiment.

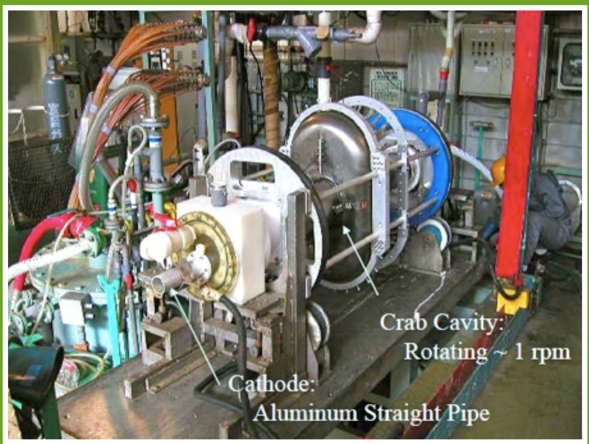
KEKB crab cavities

Starting from the baseline design Akai developed, Hosoyama drew a more detailed conceptual design with his pair of compasses, and then a technical design with CAD (mostly because his favorite compass broke). "Crab cavities were not of immediate importance for the KEKB team, and were neglected in some years," says Hosoyama. KEKB did not require crab cavity to achieve the target luminosity. A detailed simulation study at KEK later showed that crab crossing actually improves luminosity greatly. This motivated the development of crab cavities. The team persevered for thirteen years. "Persistence paid off eventually," smiles Hosoyama.

Even for Hosoyama, an expert on superconducting cavities, developing a crab cavity was difficult work. For one thing, the cavity requires an asymmetric shape, and this made the fabrication process extremely complicated. Second, the sheer size of the cavity, 1.5 meters long and 1 meter wide, was a challenge at the time of fabrication and when trying to rotate the cavity during electro polishing and rinsing.

"The coaxial beampipe was troubling," Hosoyama says. "Cooling the cavity to a superconducting temperature requires only ordinary cryogenic techniques, but cooling a pipe inside the cavity required much more: an extra cooling system." Hosoyama designed a coaxial beampipe in which liquid helium would flow in and out.

Hosoyama and his team spent years on the design of the KEKB crab cavities, producing multiple prototypes, using a test-and-modify approach. The team developed every piece of equipment necessary to fabricate, rinse, and polish these complicated structures. Superconducting meant the whole metal



Electro polishing of the crab cavity.

structure, including inner pipe, bolts and holes, had to meet at superconducting temperature. At the temperature, material volume would be significantly reduced, because the material shrinks when cooled. This made it hard to have the pieces fit together tightly. "We made a couple of trials before we finally had them perfectly fit," says Hosoyama.

Once the crab cavity was built, the focus shifted to concerns about the possibility of a helium leak. Liquid helium circulates around the system to keep the system cool. If something in this system were to go wrong, the damage could be catastrophic. "We spent some time preparing an assembly station that could fix a damaged crab cavity," says Hosoyama. "Fortunately, there were no problems with the cooling system."

The world record luminosity

Prof. Hutton recalls: "it was a disappointment when the crab cavity started." The luminosity did not go up, but rather went down. An investigation was conducted, re-examining the system from both the theoretical and the technical side. A group at KEK proposed the idea that particles with different energies may be the culprit. Generally particles' vertical motion couples with the horizontal motion (x-y coupling). The effect was corrected for the particles of design energy. In reality, the energy of the particles in a bunch varies slightly. It turns out that the x-y coupling in different energy particles cannot be taken care of by the ordinary measure.

Prof. Kazuhito Ohmi of KEK made an important contribution to this idea by carrying out the simulation of the electromagnetic effect on the beam ribbon. To fix the problem, Dr. Yoshihiro Funakoshi of KEK installed skew sextupole magnets in March 2009. These magnets correct the x-y coupling of different energy particles. The effect was enormous. The luminosity showed steep increase, from 17.6 inverse nanobarn per second to 21.1 inverse nanobarn per second.

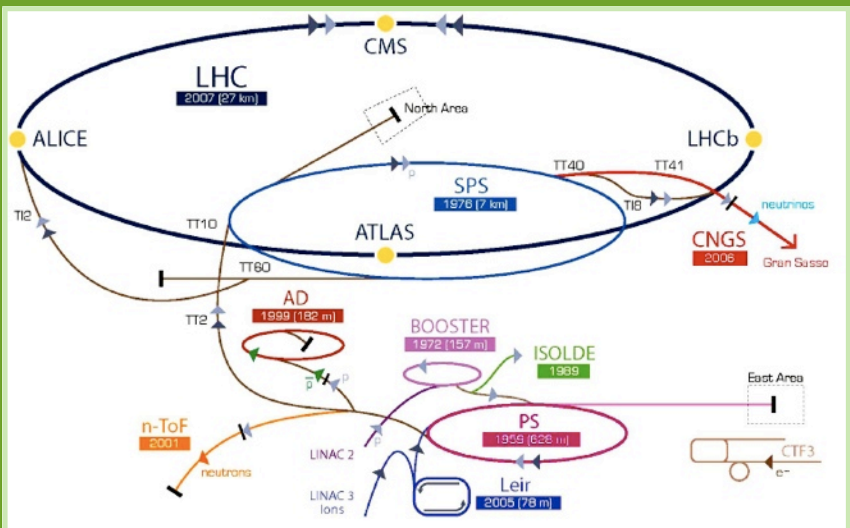
LHC crab cavity design

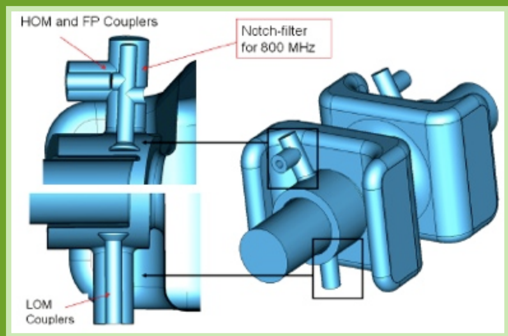
There are several different types of crab cavity. KEKB's oval shape is one. Another type is a mushroom shaped cell. Another type uses a waveguide to take out unwanted modes. Right now the LHC crab cavity team is considering all available options for the baseline design.

"Because it worked here [at KEKB], they [the LHC team] are now brave enough to take on a different design," says Prof. Hutton. The problem with the design of the KEKB crab cavities is that they are too voluminous. The beampipe separation at LHC is just 20 centimeters currently, while the KEKB type crab cavity has a widthwise dimension of 1 meter. Even though the KEKB type crab cavity is already proven to work, it is not applicable to LHC unless the size is reduced, or the beampipe separation is increased.

Meanwhile, they also plan to test the feasibility of the crab cavity scheme for the LHC upgrade using KEKB's crab cavity. When KEKB's crab cavity retires from operation before this summer, it will be shipped to CERN to be installed at the Super Proton Synchrotron (SPS) that accelerates and inject protons into the LHC.

The LHC isn't the only place that is hoping to make use of the superconducting crab cavity. From the International Linear Collider (ILC) to short pulse light sources around the world, the potential utility of crab cavities is great. Akai and Hosoyama are happy that their efforts over the past decade became fruitful. As Hosoyama says, "keep at it and be patient, and you will be rewarded."





↑The mushroom shaped cell is one candidate for the LHC upgrade crab cavity baseline design.

←CERN accelerator complex. KEKB's crab cavity will be installed at the Super Proton Synchrotron (SPS) first to test feasibility of crab cavity in the LHC upgrade.

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Development of the KEK-B Superconducting Crab Cavity

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