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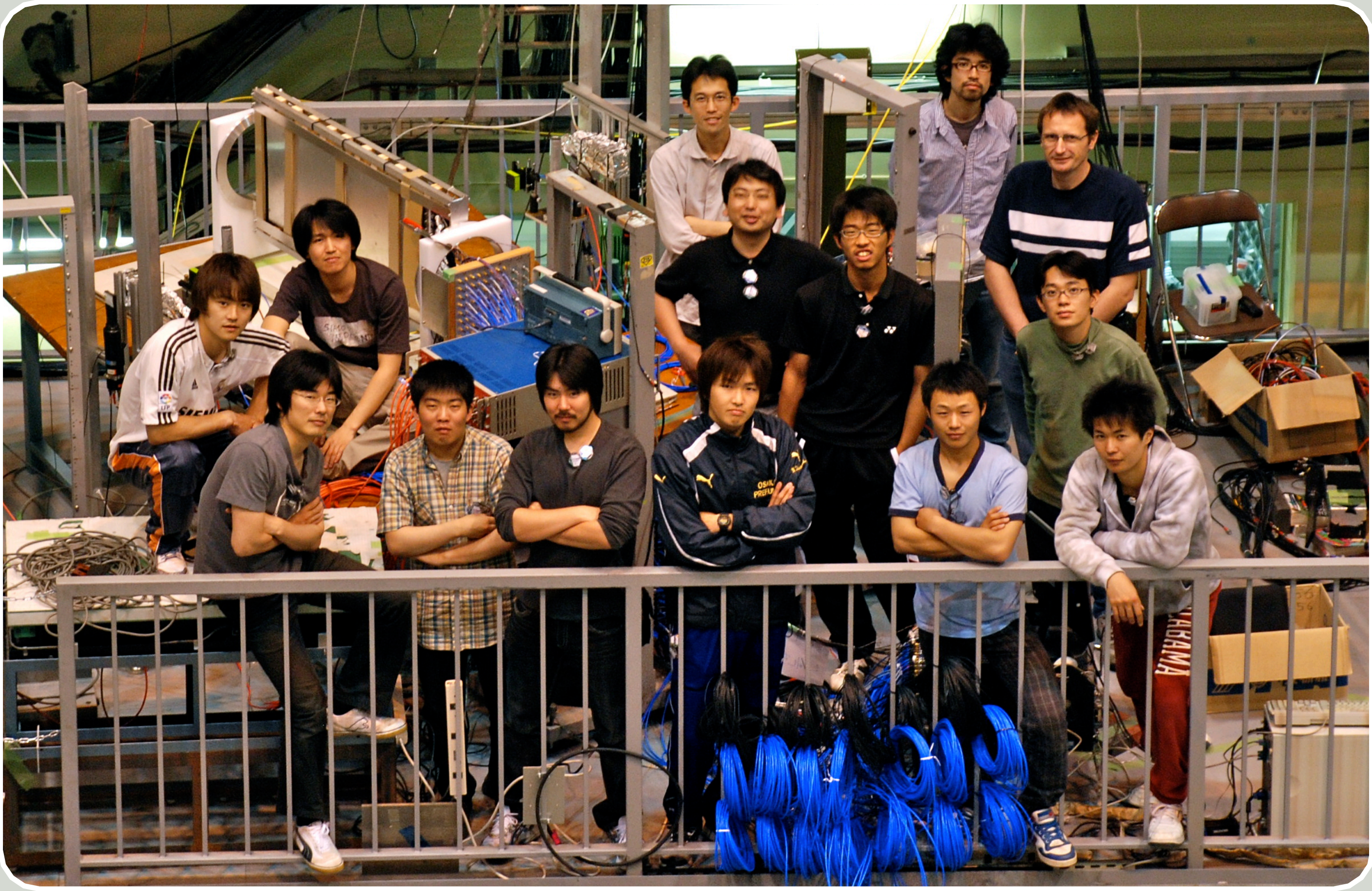
FEATURE STORY



The Belle barrel PID team during a beam test at the Fuji experimental hall at KEK. Prof. Kenji Inami of Nagoya University (middle top) is one of the two co-leaders of the team.

The TOP counter: a new method for particle identification

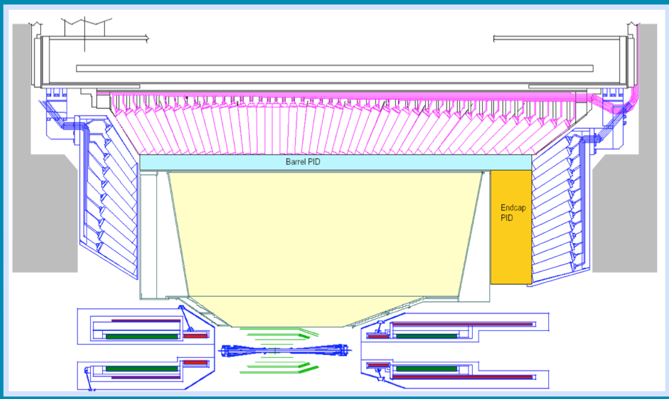
[Belle II, Particle Identification Detector, Time-Of-Propagation Counter]

The newly developed time-of-propagation (TOP) counter is starting to gather attention from the experimental particle physics community. The TOP counter is now of the baseline detector for the barrel particle identification at the next-generation B-Factory experiment, KEK's Belle II. Read on to learn more about the design of this TOP counter and the international team involved in its development.

Detecting single photons to picosecond (a trillionth second) time resolution is something like hitting a 'hole in one' in golf at a distance greater than the distance from the Moon. Yet that is the type of precision required for the photon detectors to be used in the proposed SuperKEKB-BelleII experiment. The proposed KEKB-Belle upgrade, the SuperKEKB-Belle II experiment, will have 40 times the luminosity of its predecessor. These collisions will produce many particles of unknown quark composition and energy. Many of these particles decay while flying inside the Belle II detector. The job of this mammoth detector will be to measure the properties of these particles and determine their trajectories.

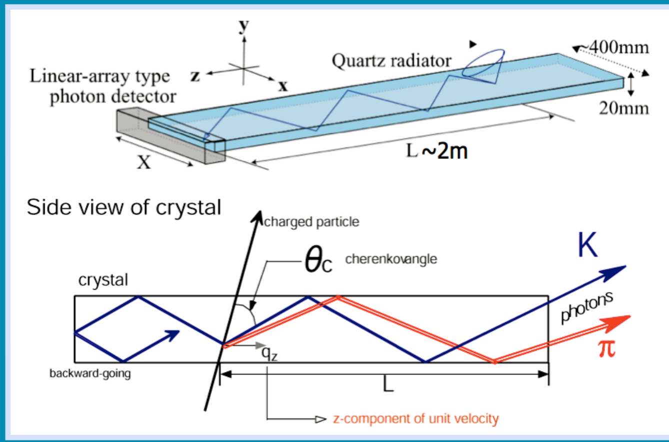
"One of the most critical things that we will be measuring is flavorful final states. That is, we want to know whether or not there are any strange quarks present in an event, in addition to the more common up and down quarks," explains one of the two co-leaders of the Belle II barrel particle identification detector (PID) team, Prof. Gary Varner of the University of Hawaii. "The easiest way to determine that is by measuring kaons."

The purpose of the PID is to identify the type of charged particles, particularly pions and kaons.



↑A cut view of the Belle II detector. The particle identification detector (PID) has two components: the barrel PID (light blue) and the forward endcap PID (orange). A time-of-propagation (TOP) counter will be used for barrel PID.

↓The TOP counter measures the emission angle of Cerenkov photons using time-of-propagation of the photons down a quartz bar to distinguish between kaons and pions.



Pions and kaons are both mesons made of a quark and an anti-quark. Pions contain only up and down quarks (or anti-quarks), whereas kaons have one of the up or down quarks replaced by a strange quark. Pions are lighter than kaons, and so travel faster than kaons for the same momentum, which is the quantity measured by the drift chamber in the magnetic field of the Belle II solenoid. Thus, one can distinguish the two particles based on their speed.

The threshold method

The Belle PID has two components: a barrel and an endcap. In the original Belle detector, high-momentum particle identification in barrel region was based on a simple black-and-white method, the threshold method. When pions and kaons travel through an aerogel radiator, they emitting light, called Cerenkov light, when their velocity exceeds the speed of light in the radiator. The emission angle depends on the index of refraction of the aerogel and on the velocity of the particles. Namely, by choosing the index of refraction of the aerogel one can design a detector in which particles slower than the speed of light in that material index would not emit Cerenkov light at all. In this carefully chosen aerogel PID, pions would emit Cerenkov light, but kaons would not.

However, kaons can interact with other detector components, giving rise to unwanted signals. The most significant of which is the interaction with the face plate of the photo sensor. To improve the detector efficiency, something more than the simple threshold method was needed.

Time-of-propagation for precise identification

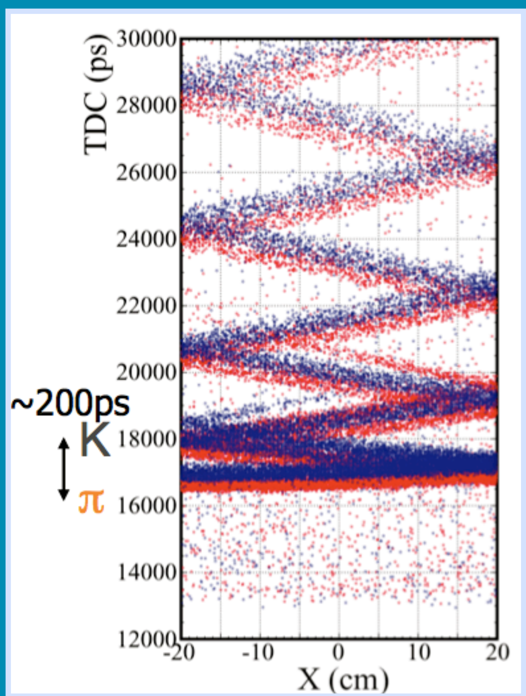
In the US, the BaBar detector at SLAC, a friendly rival to KEKB-Belle, had a more ambitious barrel PID design, the detector of internally reflected Cerenkov light (DIRC). The DIRC design uses measurements of the exact emission angle of Cerenkov light via two-dimensional hit positions on a photo sensor array. Since the Cerenkov light propagates at a speed slower than the particle itself in the quartz media, it forms a cone-shaped shock-front, just like a mach cone formed along the leading edges of a plane during supersonic flight. The Cerenkov cone then forms a ring image when projected onto an image plane. The DIRC counter projects the ring image, and by measuring the opening angle of the ring, particle types are identified.

“The DIRC was a remarkable accomplishment,” says Varner, who in the past worked on the Belle barrel PID electronics as a graduate student. “We want to take advantage of best things that were done in the BaBar effort, with two boundary conditions: one, it has to fit within the existing Belle detector, without significant change to the Belle II structure; and two, it must be affordable.”

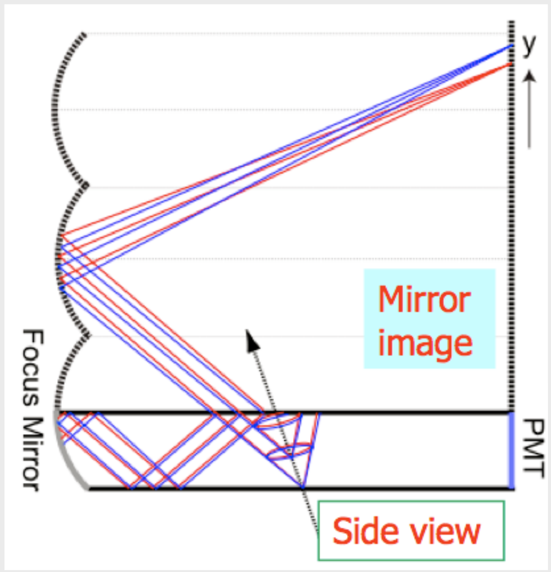
Although the upgraded version of the DIRC, the focusing DIRC, has demonstrated excellent resolution for Belle II’s barrel PID, it is too large, and would not fit within the existing Belle detector. The Belle II barrel PID needs to be compact. The Cerenkov ring developed in the quartz radiator is propagated to the ends of the bar for readout. In the endcap region, the incident particles—such as pions and kaons—usually arrive perpendicular to the detector, and there is enough space to allow the image to expand so that the ring image can be directly recorded. In the barrel region, photons can hit at nearly any angle, from perpendicular to modestly shallow. Covering the large barrel with precision sensors is financially not feasible. In the Belle II barrel PID, radial space is also much more constrained, so that the direct measurement of the Cerenkov ring is not realistic.

As an alternative to the DIRC counter, scientists at Nagoya University proposed a new, innovative idea. Instead of imaging the Cerenkov ring, they proposed to measure the emission angle of the Cerenkov light from the time-of-propagation (TOP).

Cerenkov photons emitted by particles as they travel through the quartz bar are confined within the bar by total internal reflection. They repeatedly reflect off the walls of the bar, following a zig-zag path, until they reach the



Cerenkov photons are emitted along the path of a particle inside quartz bar. The photons propagate down the bar by repeated internal reflections. The direct photons will reach the detectors first, while the reflected photons will be much slower. The horizontal axis presents the horizontal direction of the quartz bar, and the vertical axis presents time since the time of particle impact on the bar. Red dots show pions, and blue dots show kaons.



This focusing mirror was developed to compensate for the effects of chromatic dispersion on the Cerenkov photons.

end of the bar, where they are read out by photo sensors. The number of times that a Cerenkov photon is reflected before it reaches the detector is related to the angle at which the photon was emitted by the original particle. The number of reflections is, in turn, related to the time it takes for a Cerenkov photon to travel the length of the bar. This time is also known as the time of propagation. Therefore, by measuring the time of propagation, one can infer the angle of emission, and thus the type of particle.

The TOP counter was originally proposed by Nagoya University physicist Prof. Takayoshi Ohshima in 1998. A proof-of-concept TOP counter was built and tested also at Nagoya University in 2000-2001, using existing technologies. With a refined quartz bar and photo sensors, a prototype of the Belle II PID conceptual design has also been built and tested by Nagoya scientists in 2002.

The MCP-PMT, which was developed jointly by Hamamatsu Photonics Co. and the barrel PID group at the Nagoya University.

Focusing rays to improve time resolution

In principle, the TOP method can identify particles with much higher precision than the original threshold method. Unfortunately, there was one critical issue with this method. Specifically, the issue is that the speed of propagation of light inside the quartz bar differs slightly depending on the wavelength of the light. As the result, the information physicists can induce about time smears out in space, worsening the time resolution. This effect, called chromatic dispersion, had been pointed out in another Cerenkov-type counter, the correlated Cerenkov timing detector, originally developed by Ohio State University.

The solution to the problem of chromatic dispersion was proposed by Nagoya University physicist Prof.. Kenji Inami, the other co-leader of the Belle barrel PID group. He proposed attaching a concave mirror to the end of the quartz bar so that parallel rays of photons would be focused into a single pixel of a photo sensor. The chromatically dispersed rays are detected by separate channels instead of a single channel. In effect, the detector can track the time of arrival more precisely, improving the time resolution. Once realizing this, Inami immediately started simulation studies, and then built a successful prototype.

“The difference in propagation speeds due to chromatic dispersion becomes more significant as photons propagate farther,” explains Inami. “If an incident particle hits the end of the bar that is farthest away from the photo sensors, the time resolution could be as much as 250 picoseconds. The introduction of the focusing mirror reduced this error by half.”

Expanding rays to get improved spatial information

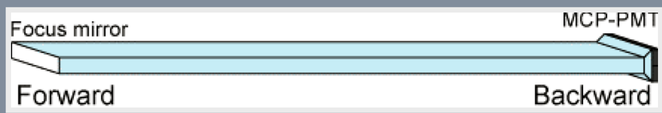
Another beautiful idea developed by the PID team was to spread out the Cerenkov rays that reached at the end of bar. This improves Belle II's ability to measure the rays’ spatial distribution. A small expansion region, called the wedge, is attached to the bar just in front of the photo sensors. This wedge permits the Cerenkov photons to spread out across the sensors at the end of the bar. In this case two rows of photo sensors, instead of a single row, are attached to the end of each module.

“We came up with this idea as a team. It seemed the natural thing to do,” says Varner. “In a pure TOP counter, the time measurement is everything. The wedge adds a little bit of additional spatial information, which helps in particle identification.”

The final TOP counter is a quartz bar, 2.5 meters in length, with a wedge attached to the photo sensor side, and a focusing mirror on the other. Two rows of 16 photo sensors are attached at the end of wedge, covering the full 45-centimeter width. There are 16 TOP modules to cover the barrel PID, which has more than 8,000 readout channels altogether.

Developing a new, high-performance photo detector

The TOP counter requires extremely high quality photo sensors. These sensors must have good timing and position resolution, high quantum efficiency, large effective area, high magnetic field tolerance, and a square shape.



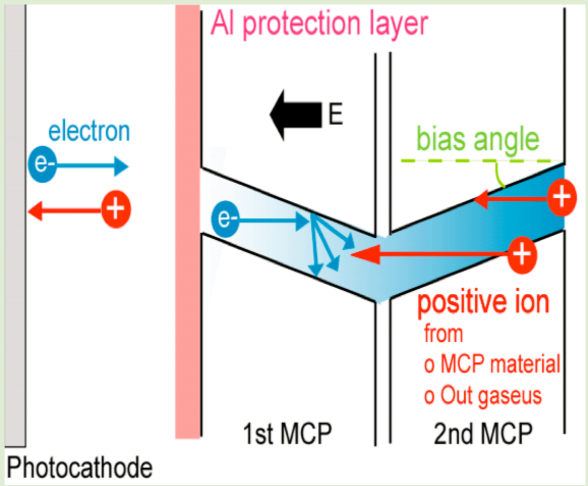
A wedge will be added to the front of the microchannel plate photomultiplier tubes (MCP-PMT) in order to gain additional spatial information about the Cerenkov light.

All previous high precision timing photo sensors had a circular shape, and none satisfied the stringent performance requirements.

In conjunction with Hamamatsu Photonics Co., the Nagoya team developed a new type of photomultiplier tube (PMT), the microchannel plate photomultiplier tube (MCP-PMT). As in a regular PMT, a photocathode converts incident photons into electrons. Within the tube, using a dynode chain in a standard tube, these original electrons are amplified to become as many as 106 electrons.

The MCP-PMT uses plates instead of dynodes for the amplification process. Each plate has many circular pores around 10-micrometers in diameter, and 30- to 40-micrometers apart. When a photon arrives, the electrons leaving the photocathode are accelerated towards the plates by an applied voltage. Electrons that enter the pores bounce along the inside of the pores, each time producing more and more electrons.

The amplification is about the same order as that of regular PMTs. The difference is improved timing. “Because the electron



In the newly developed MCP-PMT, electrons produced at the photocathode enter pores in microchannel plates (MCP) where the electrons are multiplied. This design gives significantly better single-photon time resolution than those of standard photomultiplier tubes.

amplification occurs in a very spatially confined region, the spread in transit time is very small," explains Varner. "While the transit time of electrons in a regular photon detector can vary from 0.5 to 3 nanoseconds, the range in an MCP-PMT is just 50 picoseconds or less."

One particular challenge the development team had was the short lifetime of the prototype MCP-PMT's. "Electrons produced at the photocathode can interact with residual air molecules inside the MCP-PMT, or with plate materials. These interactions then produce ions, which can return to the photocathode in the presence of high voltage, and damage the photocathode," says Inami. "This degrades the photocathode efficiency very quickly."

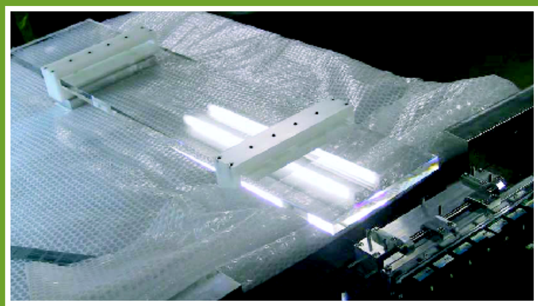
Inami and his colleagues at Hamamatsu spent three years working out a solution. They changed the internal structure of the device, and developed a cleaning process to reduce the unwanted chemical reactions of photoelectrons. A successful prototype was finally tested and proved suitable in 2008.

A large and active international team

The barrel PID team is a large international collaboration of physicists and engineers, including 10 from Nagoya University, 11 from the University of Hawaii, 7 from the University of Cincinnati, and 12 from the University of Ljubljana. The PID group is the largest international group at Belle II.

"The collaboration has tackled many issues in an analytical and critical manner, and has done so in a way that is possible only in a group with broad photo sensor backgrounds," says the barrel PID liaison and one of the co-leaders of the endcap PID group, Prof. Ichiro Adachi of KEK. "We are very fortunate to have been able to make our own decisions, without the need for external panels or committees."

The collaboration is now working towards a prototype for the detailed design of the barrel PID. It is critical to prepare for mass production of the quartz bars early. "The quartz bar surface must be flat to the order of the photon wavelengths. In this case, that means in the range of 400 nanometers to 700 nanometers," says Varner. "The manufacture of such precision quartz bars is extremely challenging, and only a few companies in the world have the equipment and know-how to do it." Zygo Co. in the US has been chosen to be one of the manufacturers of the barrel PID modules, which will be provided in two-year time.



A prototype TOP counter tested at Nagoya University.

Meanwhile, Nagoya has been working on further methods to compensate for chromatic dispersion. Since the effects of dispersion are more significant at shorter wavelengths, the team plans to implement a filter to remove photons with those shorter, more problematic wavelengths. Optimization studies by simulation, and beam test verification of the final counter design are planned.

"From detailed performance studies to actual construction, there is much work to be done," says Adachi. "We are expecting many more new researchers in our group."

A subset of the Belle II Barrel PID researchers at University of Hawaii, with co-leader, Prof. Gary Varner, second from the right.

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Address : 1-1 Oho, Tsukuba, Ibaraki 305-0801 JAPAN
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