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Particle identification with the TOP and ARICH detectors at Belle II

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ABSTRACT

The SuperKEKB e^+e^- collider will provide 40 times higher instantaneous luminosity than the KEKB collider. The Belle II detector, located at the collision point, is the upgrade of the Belle detector. The particle identification will be improved by replacing the aerogel threshold counter with two new high performance Cherenkov detectors: the time-of-propagation (TOP) in the barrel region and the focusing aerogel (ARICH) in the forward region. The time-of-propagation sub-detector consists of quartz radiator bars and micro-channel plate photomultiplier tubes. The Cherenkov photons are produced and propagated through the quartz radiator, and after multiple internal reflections they are detected by the photomultiplier tubes. Photons with different Cherenkov angles reach different photomultiplier channels and arrive at different times. The time and the position convolution is used for the reconstruction of the Cherenkov angle. The focusing aerogel consists of a double layer aerogel radiator, an expansion volume and a photon detector. The aerogel thickness and the refractive indices of the two layers are optimized to focus the two light cones at the detection surface. The key features of these two detectors, the performance studies, and the construction progress are presented.

1. Introduction

The KEK B-factory is being upgraded to SuperKEKB using the same tunnel. SuperKEKB in an asymmetric electron–positron collider based on the nano-beam scheme and high beam current with the target peak luminosity of $8 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The Belle II detector [1], located at the collision point, is the upgrade of the Belle detector [2]. At the B-factory experiments, a reliable and high performance particle identification (PID) is a key element for tagging the B meson flavor in the CP violation studies and for the efficient background reduction in rare decays of B and D mesons. At the Belle experiment the particle identification of high momentum particles was provided by a threshold aerogel Cherenkov counter. For the upgraded Belle II experiment the aerogel counter will be replaced by the time-of-propagation (TOP) [3] counter in the barrel region and by the aerogel RICH counter (ARICH) [4] in the endcap region.

2. TOP counter

The key elements of the TOP counter are the quartz Cherenkov radiator, the micro-channel plate photomultipliers, and the front end readout. The quartz radiator consists of two quartz bars glued together; the free end of one bar is terminated with a mirror, while on the free end of the other a wedge-shaped quartz block is mounted. The dimensions of the two glued quartz bars, the mirror, and the wedge-shaped quartz block are $(2500 \times 450 \times 20)\,\mathrm{mm}^3$, $(100 \times 450 \times 20)\,\mathrm{mm}^3$ and $(100 \times 450 \times 20\text{–}50)\,\mathrm{mm}^3$, respectively, where the height of wedge-shaped block varies from 20 mm to 50 mm. The radiator is supported by a quartz bar box, which consists of honeycomb panels, side rails and small buttons made of PEEK. The wedge-shaped block, the photomultipliers, and front end readout are supported by an aluminum box. The schematic drawing of the TOP counter is shown in Fig. 1.

When a charged particle passes through a material at a velocity greater than the local phase velocity of light in the material, it emits Cherenkov radiation with opening angle of the light cone depending on the velocity of the particle. In the TOP module, Cherenkov photons are created in the quartz bars, and then propagate through the bars, reflecting from the surfaces of the quartz. Photons emitted in the forward direction are reflected at the end of the bar from the mirror. Photons arriving at the end of the bar in the backward direction with different reflection angles will be collected by different PMT channels at different times. The mirror has a concave shape to partially compensate the effect of chromatic dispersion of the Cherenkov photons. The effect of the mirror is to focus parallel rays of photons into a single pixel of a photo-sensor while the chromatically dispersed rays are detected by separate channels instead of a single channel. The arriving position and time of each of the detected Cherenkov photons are

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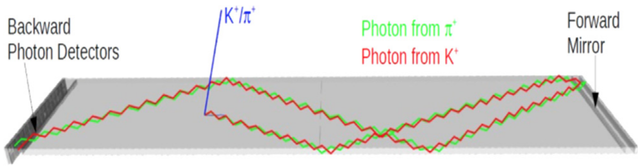

Fig. 1. Schematic drawing of the TOP counter with example of the paths taken by Cherenkov photons. The green (red) line indicates the path of a photon generated by a charged pion (kaon). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

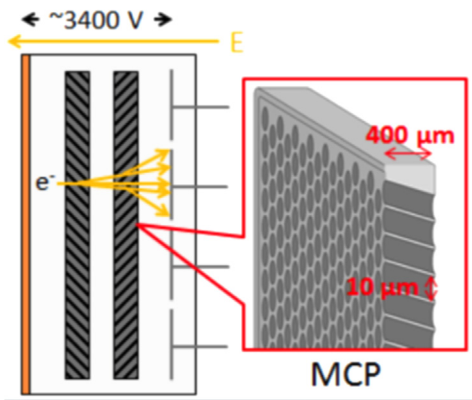

Fig. 2. A schematic drawing of the MCP-PMT.

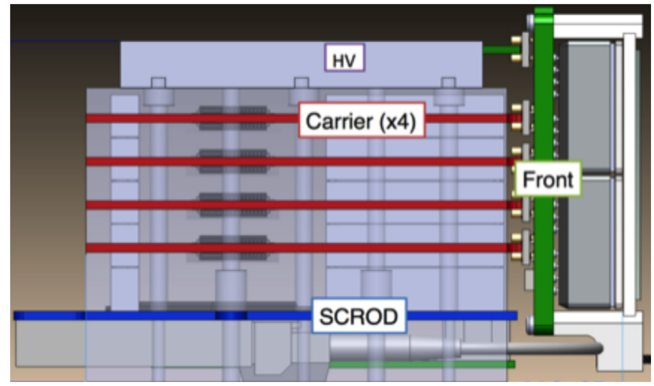

Fig. 3. Readout module for 8 MCP-PMTs.

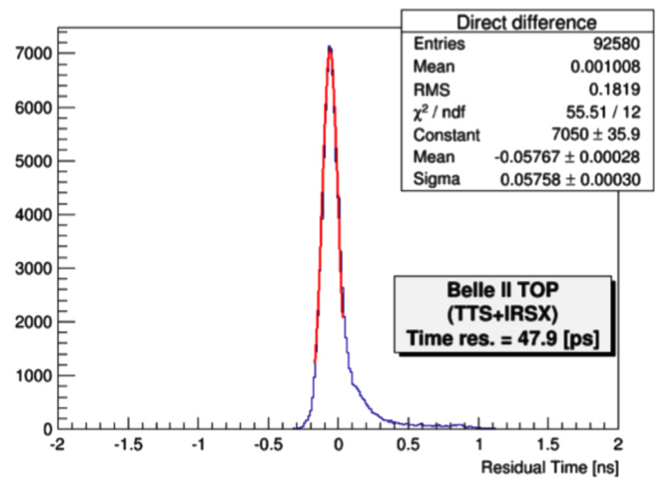

Fig. 4. Time resolution for pulsed laser irradiation. In this example the channel #0 of the ASIC #3 working with 2 10^5 gain.

used to compute a likelihood for a given particle hypotheses. To ensure optimal performance of the TOP, excellent time resolution is required for the photon detectors.

2.1. Photon detector

Because a typical time difference between 2 GeV/c $K^\pm$ and $\pi^\pm$ is about 200 ps, the time resolution for single-photon detection needs to be about 50 ps. To meet the time resolution requirement the micro-channel plate (MCP) photo-multiplier tube (PMT) has been selected as the photon detector. A MCP-PMT uses micro-channel plates as electron multipliers (Fig. 2); a two stage type achieved a gain of 10^6, and shows a fast time response.

A single MCP-PMT detector has a square shape for effectively covering the quartz-surface area and 4×4 channels in the active area of (23×23) mm^2. The Cherenkov photon is converted into an electron at the NaKSbCs photocathode. The quantum efficiency (QE) is $> 24\%$ at a wavelength of 380 nm. The produced electron is amplified by hitting the walls of the halls of two micro-channel plates. The transit time spread is about 40 ps. The lifetime of the photomultipliers is given by the time during which the QE degrades to 80% of the initial QE (a value for which the loss of performance of the TOP detector is negligible). The reduction of QE is due to the ions produced in the micro-channel plates that move backward and hit the photocathode. The average lifetime of MCP-PMT corresponds to an integrated charge of about 1.1 C/cm^2. A new technique of MCP-PMT production, named atomic layer deposition (ALD) has been recently developed. A thin aluminum layer deposed on the micro-channel surface protects the photocathode. The average lifetime of ALD MCP-PMT is about 8.6 C/cm^2. Specific studies have been performed to improve the deposition technique, the selected one (improved ALD) has the lower life time spread. For the 16 TOP modules, 512 photomultipliers plus spares are needed. The available photomultipliers are 568 ($\sim$50% conventional MCP-PMT and $\sim$50% ALD MCP-PMT).

2.2. Front end readout

The Cherenkov photon signal from the MCP-PMTs is read out using waveform-sampling ASICs [5]. Every 4 GHz ASIC chip can read 8 channels. Four chips are attached on a carrier board, and four carrier boards form a readout module (Fig. 3). A readout module corresponds to 8 MCP-PMTs.

The time resolution for this readout system is measured to be about 50 ps (Fig. 4).

2.3. Control and calibration systems

In the box supporting the wedge-shaped quartz, 8 LEDs and 8 CCDs will send and receive the light to control the quality of the optical coupling between quartz and PMT. In the same box 9, terminal optics of the laser calibration system are placed between the CCDs and at the two extreme sides. The optics are micro-graded index lenses, which spread with half angle of about 30° the pulsed light sent by a laser source into all the channels. The calibration system will be able to control the MCP-PMT and the front end electronic stability and to measure the relative QE of PMTs. In Fig. 5 the picture of the box supporting the wedge-shaped quartz, with the control and calibration systems installed, is shown.

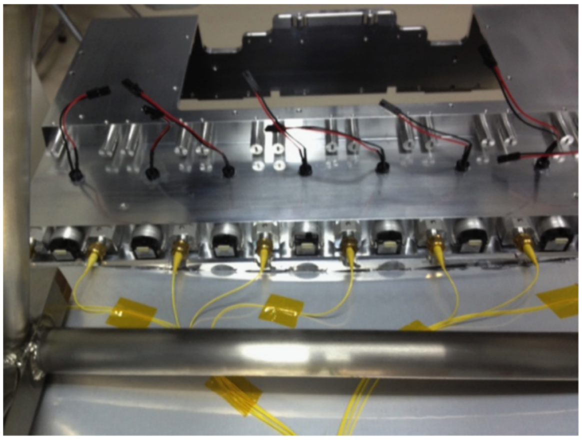

Fig. 5. LEDs and CCDs of the control system and fiber bundle with terminal optics of the laser calibration system.

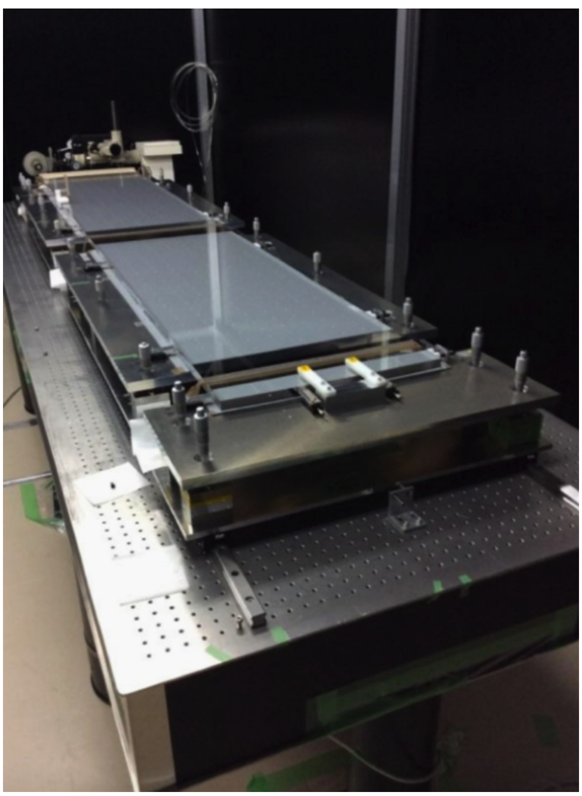

Fig. 6. Module #4 inside the clean room at the end of the quartz gluing.

2.4. TOP construction

The quartz needs to be of high quality to ensure that any photon losses during propagation through the bar are small, and that the Cherenkov photons maintain their reflection angle though many reflections from the surfaces of the quartz. All the quartz bars satisfy the quality control conditions. For the surfaces of the radiators, the conditions are flatness $<6.3\ \mu\text{m}$, roughness <0.5 nm, perpendicularity <20 arcsec, and parallelism <4 arcsec. The gluing of the quartz components and the assembling of the first module started on October 2014. Currently, four modules have been assembled and one module is equipped with the electronics. Fig. 6 shows module #4 at the end of the quartz gluing. The production of the TOP modules reached the expected rate of one module every three weeks and will be completed in March 2016.

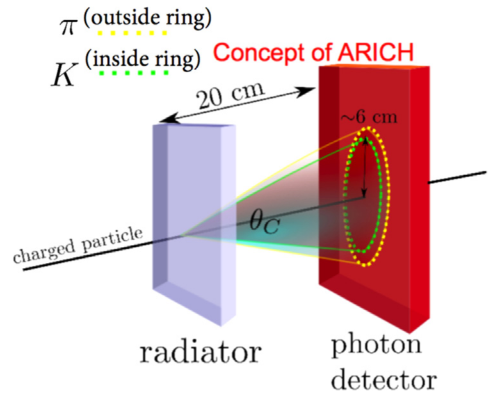

Fig. 7. The concept of the ARICH.

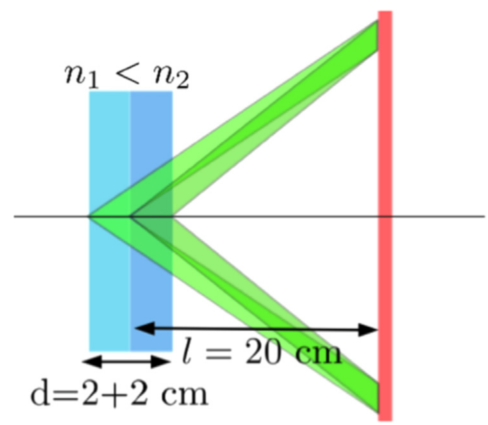

Fig. 8. The proximity focusing technique.

3. ARICH

The ARICH detector identifies a charged particle by measuring its Cherenkov angle emitted in aerogel radiator (Fig. 7). The aerogel radiator consists of 2 layers with different refractive indices and proximity focusing technique (Fig. 8). The focusing is obtained by optimizing the aerogel thickness (20 mm per layer) and the refractive indices ($n1=1.045$, $n2=1.055$). With such a configuration, approximately 10 photons per charged track, with the Cherenkov angle resolution σ_{θ_c} of about 13 mrad, are detected on the detector plane for high momentum particles. This is to be compared with a single, twice as thick, radiator layer where similar number of photons is detected, but σ_{θ_c} is about 20 mrad. The aerogel tiles are wedge shaped and have a size of $\sim 18 \times \sim 18$ cm. The whole ARICH consists of 2 124 aerogel tiles arranged in four concentric rings.

3.1. HAPD

A newly developed Hybrid Avalanche Photo Detector (HAPD) will be used as photo detector. It provides high single photon detection efficiency with the desired position resolution. The principle of HAPD operation and its scheme are shown in Fig. 9. The incident photon is converted into photo-electron by a bi-alkali photo-cathode, with peak quantum efficiency of 28% at 400 nm. The electron is then accelerated in a vacuum tube with high electric field towards the segmented avalanche photo-diode with 144 pads of size $(5.1 \times 5.1)\ \text{mm}^2$. The ARICH consists of 420 HAPD modules arranged in seven concentric rings.

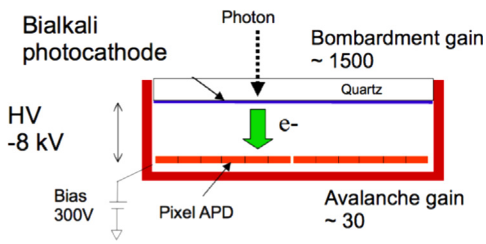

Fig. 9. Principle of HAPD operation.

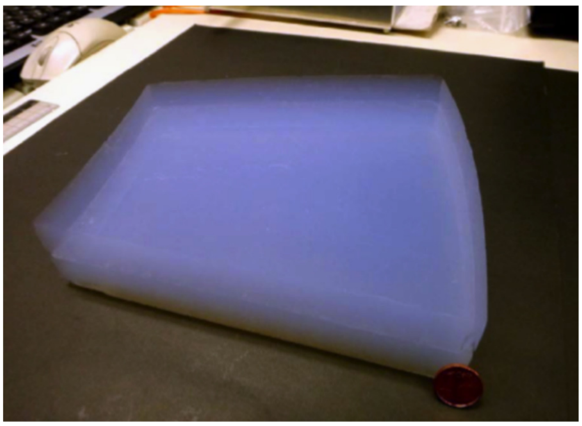

Fig. 10. Fan-shaped aerogel tiles.

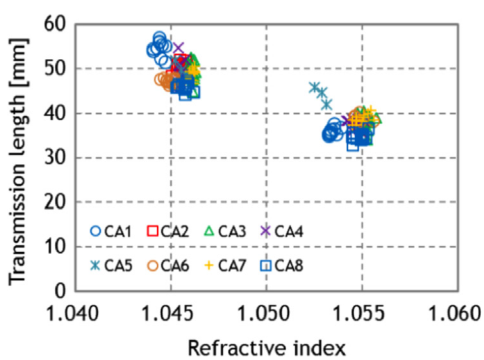

Fig. 11. Transmission length of the produced aerogel tiles as a function of the refractive index.

3.2. *ARICH production*

The mass production of the aerogel tiles is finished. In Fig. 10, two fan-shaped aerogel tiles with dimensions $\sim(18\times 18\times 2)\ \mathrm{cm}^3$ are shown.

The produced tiles have the desired transmission lengths (TL) and refractive indices (n) with fluctuation of $\pm 10\%$ for TL and $\pm 5\%$ for $n-1$ as shown in Fig. 11. The mass production of the HAPD is at 87% and will be completed by September 2015.

4. Conclusion

The Belle II experiment will be equipped with 2 new PID detectors: the TOP and the ARICH. The TOP quartz components have been produced with the expected time schedule and with the required specifications. New MCP-PMTs (ALD) with a life time increased by a factor 10 have been developed. The TOP Module #1 is complete and under test at the cosmic ray telescope, 4 modules have already been assembled, and the production will be finished by March 2016. The mass production of the aerogel tiles to be installed in the ARICH is finished. The produced tiles have the desired transmission lengths and refractive indices, with limited fluctuations. New HAPD photon detectors with high single photo-resolution and high segmented avalanche photo-diode have been developed. The production of HAPD is ongoing and will be completed by September 2015.

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