Calibration and Commissioning of the Time Of Propagation PID Detector at the Belle II Experiment

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Abstract

The Time Of Propagation (TOP) counter is a novel particle identification detector which relies on the precise detection time of Cherenkov photons produced by charged particles traversing a quartz bar. The TOP counter is constituted by 16 modules that cover the barrel region of the Belle II detector. Each module is instrumented with 32 Micro-Channel-Plate Photo-Multiplier-Tube (MCP-PMT) detectors, which are read out by dedicated fast waveform-sampling front-end electronics. After recalling the performance goals and stringent design requirements of the TOP counter, a comprehensive overview of its calibration strategies will be given. The status of the integration with the other Belle II sub-detectors and the performance during the commissioning phase with cosmic ray data will be presented, along with a preliminary study of the first SuperKEKB collision events.

Keywords: Particle Identification, Cherenkov Detector, MCP-PMT photosensors
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1. Introduction

The Belle II Experiment [1] at the KEK Laboratory in Tsukuba, Japan, is dedicated to the detection of effects of Physics beyond the Standard Model through the study of the decays of B and D mesons and of τ leptons, of the production of exotic particles, and in general of any discrepancies from the expectations in observables for which the Theory can provide precise predictions. It is going to study the e^+e^- collisions produced by the SuperKEKB [2] accelerator, which will operate at a center of mass energy corresponding (or close) to the mass of the $\Upsilon(4S)$ resonance, at the unprecedented target luminosity of $8 \cdot 10^{35}$ cm^{-2}s^{-1}. The Belle II detector consists of silicon vertex trackers for the precise determination of decay vertices, a drift chamber for the tracking and measurement of the specific energy loss (dE/dx) of charged particles, an electromagnetic calorimeter with good hermeticity, and a detector for muons and K_L^0 particles.

In addition to the above mentioned subdetectors, two Particle Identification (PID) devices will be devoted to the precise identification of charged hadrons: the ARICH, covering the forward endcap region of Belle II, and the TOP, located in the barrel region. The combined PID performance aims at achieving a K (π) identification efficiency of 95%, with a corresponding π (K) mis-identification probability of 5% for momenta as high as 4 GeV/c.

2. The Time Of Propagation Counter

The Time Of Propagation (TOP) counter relies on the emission of Cherenkov light of a charged particle traversing a dense transparent medium. The aperture angle of the cone of the emitted photons is related to the velocity β of the incident particle so that, combining this information with the momentum measured by the tracking devices, the most likely mass of the candidate particle can be inferred.

The TOP counter consists of 16 identical modules (see Fig. 1), each consisting of two two $1250 \times 450 \times 20$ mm bars, which form a 2500 mm long bar, a prism at one end of the bar, and a focusing mirror at the other end. The Cherenkov photons emitted by a charged particle either propagate towards the prism or are reflected towards it by the focusing mirror.

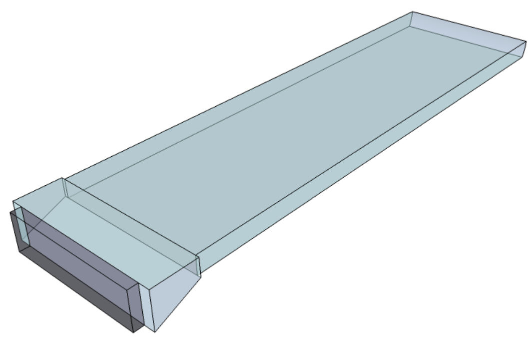

Figure 1: Schematic view of one TOP module.

The number of reflections and thus the time of propagation of the photons through the bar is determined by the original opening angle and ultimately by the velocity of the incident charged particle. Figure 2 shows the comparison of the different patterns produced by a π and a K particle for a given momentum

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and point of incidence of the candidate particle. As it can be clearly seen, the main difference between the two distributions consists in a shift along the time axis.

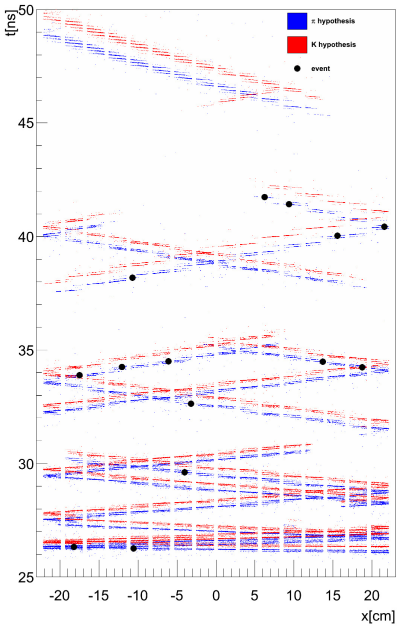

Figure 2: Comparison of the expected patterns for a charged particle of given momentum and point of incidence on the TOP bar, in case it is a π (blue) or a K (red). The vertical axis represents the time of detection of the photons, while the horizontal axis corresponds to the coordinate of the detected photon hit along the width of the bar. The black dots correspond to the photons that are detected in a typical event (a pion in this example).

The fundamental requirement for the TOP counter is thus to be able to determine the time of propagation of the Cherenkov photons with a very small uncertainty. In order to reach the target precision, the uncertainty on single photon detection needs to be $<$ 100 ps.

3. Photosensors and Front End Electronics

A charged track traversing a TOP module on average produces only $O(100)$ photons that can reach the photosensors. Besides having excellent time resolution, it is thus fundamental that the photosensors can operate in the single photon regime and have good Quantum Efficiency (QE). Moreover, the sensors must operate in the 1.5 T magnetic field provided by the solenoid of the experiment and survive the harsh background conditions of the SuperKEKB Collider.

The chosen photosensor is a micro-channel-plate photomultiplier tube (MCP-PMT) manufactured by Hamamatsu Photonics K. K. [3]. The outer size of the front face of the device is 27.6 $\times$ 27.6 mm^2 (the photochathode being 23 $\times$ 23 mm^2) with 4 $\times$ 4 readout channels. Each TOP module is instrumented with two rows of 16 MCP-PMT's (512 readout channels per module). The sensors are initially operated at a gain of 5 $\times$ 10^5 (but we plan to reduce it to 2.5 $\times$ 10^5 in order to extend their lifetime), the transit time spread is less than 40 ps, and the average QE is 28%, peaking at a wavelength of around 360 nm.

Given that the predictions on the levels of the machine backgrounds have sizably increased since the start of the development, a significant effort has been produced in order to extend the lifetime of the MCP-PMTs [4]. Despite this, the first produced photosensors (about one half of the total) will need to be replaced, most likely during the 2020 shutdown.

Severe constraints are placed also on the Front End Electronics (FEE). To reach the goal on the time resolution, each readout channel is sampled at 2.7 GHz, with 12 bit resolution, which translates to 265 Tbit/s for the whole TOP detector. The pedestal subtraction and the identification of the photon hits must be performed online by the Front End Electronics. An Application Specific Integrated Circuit (ASIC) has been developed by the University of Hawaii [5] and it is meeting all the very stringent requirements, including those on power consuption (the FEE must operate in the very tight space constrained by the presence of other subdetectors, with limited cooling capabilities).

4. Calibration Overview

In order to calibrate to the required precision each channel of the TOP detector, a procedure consisting of the following steps is carried out:

1. local T_0 calibration;
2. module T_0 calibration;
3. geometrical alignment;
4. common T_0 calibration.

The **local** T_0 calibration aims at aligning in time all the channels of a TOP module, subtracting all the effects arising from different cable lengths and differences in the response of the electronics. The procedure is performed using the laser calibration system, which flashes pulses of laser light against the tilted face of the prism, from 9 light sources on each module. The laser light, provided by a *picosecond laser*, is divided by a Planar Light Circuit (PLC) and carried by 16 ~25 m long single-mode fibers to the vicinity of each TOP module, where it is further split into 9 multi-mode fibers that terminate into a GRIN lens, which uniformly diffuses the light towards the MCP-PMT's. The main difficulty of this calibration step arises from the fact that every channel can receive light from more than one source and the photons can reach the target channel following different paths, sometimes producing a very complicated structure in the observed signal. To correctly reproduce these effects, intensive use of the simulation is made. Due to the still imperfect modeling of all these subtle effects, the average precision of the local T_0 calibration is still ~100 ps.

After completing the local T_0 calibration, the **module** T_0 step ensures that all modules are aligned to the same time reference. This calibration is performed by selecting cosmic events in which the cosmic track passes through two TOP modules. Taking into account the time of flight between the two modules and correcting for the expected differences in the times of propagation of the photons inside the different modules, a χ^2 fit is set up to determine the unknown T_0 offsets. Choosing one module as reference, and having more module pair combinations than unknowns, the procedure converges, with a preliminary uncertainty of 30-50 ps, mostly depending on the number of cosmic tracks incident in a particular TOP module (modules on the sides see less cosmic events, compared to those at the top or bottom of the barrel). This procedure is cross-checked with the laser system (where the uncertainty arises from potential differences in the length of the optical fibers carrying the light to the modules). Figure 3 shows the very good agreement between these two methods.

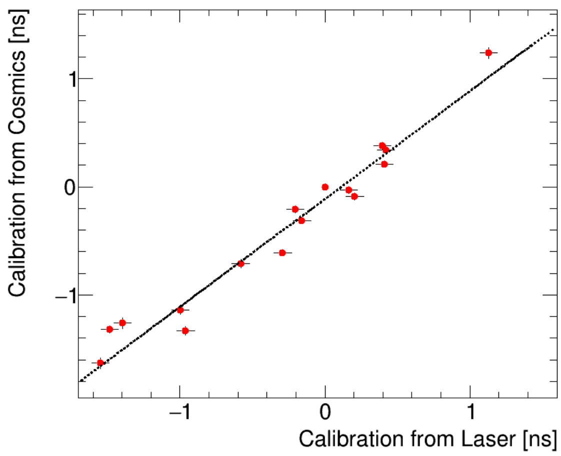

Figure 3: Results of the module T_0 calibration from cosmic data (vertical axis) versus the calibration using the laser system (horizontal axis). One of the modules is taken as reference (point at (0, 0)).

As the PID performance of the TOP counter strongly depends on the determination of the impact point where the candidate particle hits the quartz bar, it is necessary to precisely determine the position of each TOP module in the Belle II coordinate system. This is the goal of the **geometrical alignment**. This procedure uses $e^+e^- \rightarrow \mu^+\mu^-$ events to iteratively compute a PID likelihood (using the muon hypothesis) [6], varying three displacements about the coordinate axes Δx, Δy, and Δz, and three rotation angles about the same axes: α, β, and γ. We allow for a further T_0 correction with respect to what found in the previous step (which assumes the detector position to be the nominal one). At the time of writing this contribution, an adequate sample of di-μ events (we require at least 10000 tracks per module) has not been collected yet. The procedure has been attempted using the cosmic events collected in the Winter of 2018. Despite additional uncertainties arising from the different topologies (for the modules in the upper half of the barrel the track typically traverses the bars in the opposite direction, compared with what one has in collision events), and the uncertainty in determining the T_0 of the event, the initial campaign confirms the nominal geometry with an uncertainty of $\sim$1 mm in the displacements and $\sim$1 mrad on the rotation angles. The procedure on the collision data is expected to yield a $\times 3$ better precision.

Finally, the **common T_0 calibration** aligns in time the TOP counter with the other subdetectors of Belle II. Since the PID capabilities rely on the precise determination of the time of propagation of the photons from the point in which they are generated, any time misalignment (particularly with respect to the tracking devices) would degrade the performance. The calibration is performed using e^+e^- collision data, selecting events containing exactly two reconstructed tracks, computing the PID likelihood for them, and finding the time for which the sum of the two likelihoods is maximum. With the first collision data, this step proved to be slightly more problematic than expected, resulting in a 10-20 ps bias which can be measured by comparing the results of the procedure on two track events and in multitrack events. The main cause for this discrepancy is not fully understood yet, but we believe that with a clean high-statistics $e^+e^- \rightarrow \mu^+\mu^-$ sample (which is not yet available at the time of writing), the bias can be eliminated and a precision of a few ps can be obtained.

The combined precision of the current TOP calibration is at the level of $\sim$150 ps, still not adequate for the target PID capabilities of the detector. Part of the poor performance is due to the low quality and statistics of the data samples at hand, while the remaining part is due to areas in which further improvement is needed (and achievable). At the moment, there are no identified problems that could prevent the TOP counter from reaching the required precision.

5. Performance on Cosmic Events

Since Summer 2017, the TOP counter regularly participated to the Global Cosmic Runs with the other Belle II subdetectors, with the aim of testing the DAQ infrastructure, debugging each subsystem, and collect data useful for the calibration and the performance assessment.

In Winter 2018, weeks before the beginning of the operations of SuperKEKB, the Belle II detector collected a sample of more than 50 million cosmic events. Figure 4 shows an example of a cosmic event in which a muon traverses two TOP modules, and shows the agreement between the expected times of arrival of the photons and those of the actually detected photons. The event T_0 (defined as the instant in which the incident particle crosses the horizontal plane that contains the designated e^+e^- interaction region) can be determined from each single TOP module, by maximizing the PID likelihood for a given particle hypothesis (muon for cosmic rays traversing the whole Belle II detector). The uncertainty on this estimation (which can be measured by comparing the T_0's computed by two modules hit by the same track) is of the order of a few tens of ps.

Figure 5 shows the $K-\mu$ separation capabilities of the TOP counter on cosmic data. Despite the non perfect status of the calibration, and the additional uncertainty on the estimation of the event T_0, we can already achieve good separation, at least for momenta lower than 2 GeV/c.

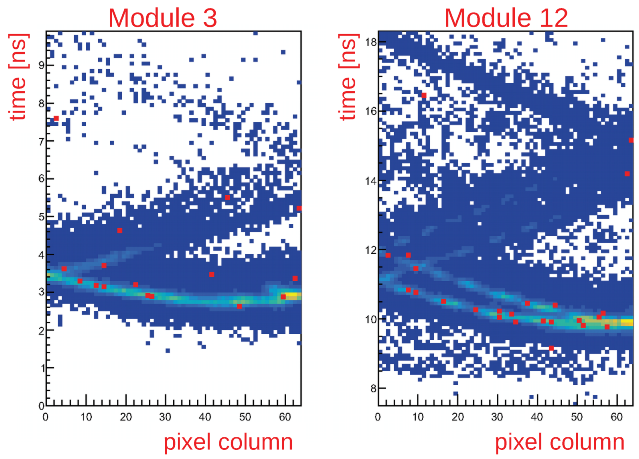

Figure 4: Detection time (vertical axis) versus pixel column (which expresses the position along the width of the TOP bar, horizontal axis) for a cosmic track traversing TOP modules 3 (left) and 12 (right). The colored bands represent the expected times of arrival of the photons for the measured momentum and impact point of the track, in the hypothesis that it is a muon. The red dots correspond to the actually detected photons.

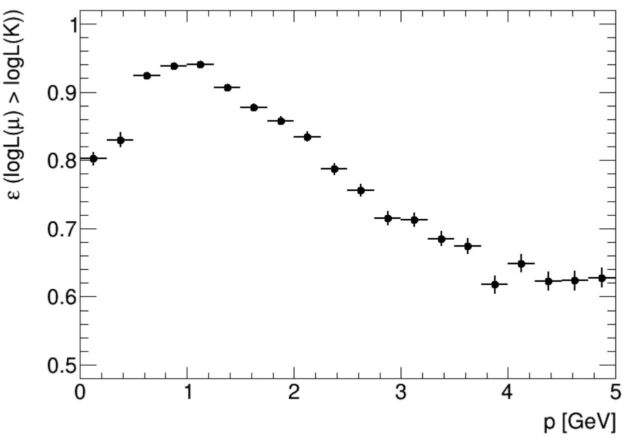

Figure 5: $K - \mu$ separation on cosmic ray data: the difference between the likelihood calculated using the μ hypothesis and the likelihood using the K hypothesis for the same cosmic particle as a function of its momentum.

6. Performance in Collision Data

Since the first SuperKEKB collisions, the TOP counter regularly participated to the data taking runs of the Belle II Experiment, with only minor disruptions due to DAQ instabilities or other problems.

The first priority for the TOP group was to assess that the machine background conditions are safe for the high voltage operations of the MCP-PMT's. While there is no immediate threat for the safety of the detector, the initial runs proved that the machine background is significantly higher than what was predicted by the simulation, even taking into account the expected improvements in the conditions of the vacuum in the beam pipe. With beam currents still about one order of magnitude smaller than the design value (and luminosities of the order of 10^{33} cm^{-2}s^{-1}), the typical noise rate is $\sim$ 500 kHz/PMT (the maximum tolerable rate being 2 MHz/PMT). Without a substantial reduction of the background rate in the future data-taking phases of the Experiment, the lifetime and performance of the TOP counter (and of other Belle II subdetectors) could be put in serious question.

Only very preliminary and low statistics studies of $K - \pi$ separation capabilities based on $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ samples. The initial indications from these studies is that, for the target K (π) identification efficiency, the π (K) misidentification probability is a factor 2-3 higher than the value expected from the simulation.

7. Conclusions and Outlook

The TOP counter is a very challenging novel PID detector, which is expected to strongly contribute to the success of the Belle II Experiment. The construction and the initial commissioning of the device have been successful, and after the initial calibration, its performance is reasonable. The target of $<$ 100 ps uncertainty per channel for single photon detection is yet to be achieved, but the TOP group is confident that with high statistics and clean $e^+e^- \to \mu^+\mu^-$ samples and better modeling of the complicated time structure of the photon distributions the challenge can be met.

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