A scintillator based muon and $K_L$ detector for the Belle II experiment

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Abstract: A new muon and $K_L$ detector based on scintillators will be used for the endcap and inner barrel regions in the Belle II experiment, currently under construction. The increased luminosity of the $e^+e^-$ SuperKEKB collider entails challenging detector requirements. We demonstrate that relatively inexpensive polystyrene scintillator strips with wave length shifting fibers ensure a sufficient light yield at the Silicon PhotoMultiplier (SiPM) photodetector, are robust and provide improved physics performance for the Belle II experiment compared to its predecessor, Belle.

Keywords: Solid scintillator detectors; Particle tracking detectors; SiPM; Muon detector.

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1. Overview

Over the last decade, the B-factory experiments, Belle and BaBar, have demonstrated that flavor physics has the powerful potential to search for various manifestations of New Physics. If the statistical errors of measurements in the flavor sector can be substantially improved, the energy scale of New Physics studies can be pushed beyond 1 TeV, providing strong impetus for construction of the next generation B-factory. The idea of an upgraded Belle experiment was first presented in a Letter of Intent in 2004 [1], followed by a Technical Design Report in 2010 [2]. In parallel, the KEKB accelerator group has defined the parameters of the SuperKEKB accelerator, an upgraded version of KEKB, with luminosity increased by almost two orders of magnitude, and an ultimate instantaneous luminosity goal of $8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$. Currently the SuperKEKB Factory, and the associated Belle II sub-detectors are under construction at the High Energy Accelerator Research Organization, KEK, in Tsukuba, Japan. This new installation is expected to start operation at the end of 2015 with the expectation of collecting an integrated luminosity of 50 ab$^{-1}$ by 2020.

The $K^0_L$ and muon subsystems (KLM) in the Belle experiment were designed to detect $K^0_L$ mesons and muons as they traversed the segmented flux return of the Belle solenoid, using resistive plate chambers (RPC) [3, 4]. The KLM system has a cylindrical (barrel) part and two planar endcap...
The RPC KLM detector operated successfully over the entire lifetime of Belle (1999-2010). However, the endcap and inner barrel gas detectors of the Belle II experiment will suffer considerably compromised performance in the higher luminosity SuperKEKB environment, given the higher backgrounds and the long RPC dead times. This requires development of a new detection technique, which should be robust, inexpensive and capable of coping with high backgrounds.

In this paper, we present a scintillator-based solution for the Belle II KLM detector and demonstrate that it matches the scientific and environmental requirements. The possibility to use this technology was first discussed in a previous paper [5], which was then chosen as the baseline technology for Belle II. The construction of the new KLM detector is already underway. A similar approach was also proposed for SuperB experiment in Italy [3], which has since been, quite unfortunately, canceled.

2. The Belle II endcap KLM system

Scintillator counters with wave-length-shifting (WLS) fibers as an option for the endcap KLM was first proposed by our group in the Belle upgrade Letter of Intent [1]. Charged particle detection with such detectors, usually equipped with photomultiplier tube (PMT) readout, is a well-established technique [7, 8]. However, in the case of the Belle II detector, the limited space and strong magnetic field do not allow use of PMT’s. As an alternative photodetector, we proposed multipixel silicon photodiodes operating in the Geiger mode, originally developed in Russia [10] in 1990s, and currently produced by many companies under different names: SiPM, Avalanche Photo-Diodes (APD), Metal-Resistor-Semiconductor (MRS), Multi-Pixel Photo Counters (MPPC), Multi-Pixel Avalanche Photo-Diodes (MAPD), etc. In this paper, we will use a generic name SiPM (Silicon PhotoMultiplier) to describe all such detectors.

SiPM’s allow for compact detectors and uncompromised operation in strong magnetic fields. The first large scale (8000 channels) SiPM application was the CALICE’s hadron calorimeter [11, 12] which demonstrated the feasibility to use SiPM’s in real experiments as well as their advantages over traditional PMT’s. The use of SiPM’s in a real experiment with a huge number of readout channels (∼ 100k) began with the near detector of the T2K experiment [9], where many subsystems are based on SiPM read out of scintillator light. However, the background and radiation environment as well as space constraints in neutrino experiments are much more benign, and much more tests required to prove the applicability of this technique to the Belle II experiment.

2.1 General layout

The base element of the proposed detector system is a scintillator strip of polystyrene doped with a scintillator die. It has a rectangular cross-section and a varying length of up to three meters to pave a sector. The strip height is limited to 10 mm by the mechanical constraints of the gap in the iron yoke and frame structure. The selected strip width of 40 mm is a compromise between the total number of channels and the required spatial resolution for muon and $K^0_L$ reconstruction. The granularity is similar to the average granularity of the Belle experiment’s original RPCs. It is commensurate with the uncertainties due to muon multiple scattering and typical hadron shower transverse sizes; further increase of the granularity practically does not improve muon identification performance and $K^0_L$ angular resolution.
The schematic of the assembled strip is shown in Fig. 1. Individual strips are covered with a diffuse reflective coating; each strip has a groove in the center to accommodate a WLS fiber. Scintillator light is collected by a WLS fiber and transported to the photodetector. Each WLS fiber is read out from one side – the far end of the WLS fiber is mirrored to increase the total light yield from the strip. To increase the efficiency for light collection, the WLS fiber is glued to the scintillator, with the SiPM then coupled to the fiber end, and fixed and aligned with the fiber using a plastic housing.

One ‘superlayer’ is formed from two fully overlapping orthogonal layers, each containing 75 scintillator strips. The independent operation of two planes in one superlayer should reduce the combinatorial background in comparison with the present RPC design where every background hit produces signals in both readout planes. Scintillator strips are arranged in a sector, with a geometry matched to the existing gap in the iron yoke, as shown in Fig. 2. 15 strips are glued to a common thin (1.5 mm) polystyrene substrate from both sides and fixed in the support profile. In addition to providing rigidity and moderate passive neutron shielding, this substrate also serves to absorb protons scattered by background neutrons, and thereby prevent correlated hits in two layers appearing from a single background neutron. The sector frame is identical to that used for Belle’s RPC mounting. The dead zone around the inner arc is estimated to be \( \sim 1\% \) of the total sector area due to the inscription of the rectangular structure into the circular housing. The inner dead zone is approximately the same as that of the Belle RPC KLM detector. Around the outer circle, the dead zone is 4\%, primarily owing to the presence of front-end electronics and cables, but also realizing that the extremely short strips that would be installed there have very small coverage, and do not justify the additional number of read-out channels they would entail. (We note that the acceptance loss at large radii is not critical for muon and \( K^0_L \) reconstruction.) In the middle part of the sector, unavoidable small dead zones (0.8\%) are due to the presence of support structures. The total insensitive area between strips due to the reflective cover is only 0.3\%. In total, the geometrical acceptance of the proposed system is slightly better than that of the Belle RPC KLM.
In the proposed KLM system the scintillator-based superlayers are installed in all 14 gaps in the magnet yoke in both the forward and backward endcaps. The whole system consists of 16800 scintillator strips of different lengths.

### 2.2 SiPM’s, detailed description

A SiPM is a matrix of tiny photo-diodes (pixels) connected to a common bus and operating in the Geiger mode [10]. A photo of the SiPM’s surface from different vendors is shown in Fig. 3. Usually the number of pixels is $\sim 100 – 1000$ over a typical area of $1 \times 1$ mm$^2$. Connection to the common bus is done usually by a $\sim$MΩ resistor. This resistor limits the Geiger discharge developed in a pixel by photo- or thermal electrons. In this mode, the SiPM response depends on the number of fired pixels and is proportional to the initial light, as long as the number of fired pixels is much less than the total number of pixels.

**Figure 2.** One superlayer formed by scintillator strips. Sizes are given in mm.

**Figure 3.** Microscopic views of SiPM surfaces from different manufacturers: a) Hamamatsu (MPPC S10362-11-050C, $1.3 \times 1.3$ mm$^2$), b) CPTA (CPTA 143, $d = 1.3$ mm), c) MEPhI/PULSAR ($1.0 \times 1.0$ mm$^2$).
As compared with conventional vacuum photomultipliers, SiPM’s have lower operating voltages, typically of order several tens of volts, which is higher than the breakdown threshold by (typically) several volts. The values of the overvoltage and the capacitance of a single pixel determine the photo-detector gain (typically of order $10^6$). The values of quenching resistance and the capacitance of a single pixel determine the dead time of a pixel, which is typically $\sim 10 - 100$ ns. The photon detection efficiency (PDE) depends on the overvoltage and reaches $30 - 40\%$ for modern devices. SiPM’s with a smaller number of pixels have higher PDE values owing to the smaller non-sensitive area between pixels. The insensitivity of SiPM’s to magnetic fields was checked in fields up to 4 T [15].

Among the disadvantages of SiPM’s are the high levels of noise ($\sim 10^5 - 10^6$ Hz/mm² at the 0.5 p.e. threshold), an optical inter-pixel cross talk producing a tail of higher noise amplitudes, and high sensitivity of the SiPM response to ambient temperature, since the breakdown voltage depends on temperature ($\sim 60$ mV/K for Hamamatsu, $\sim 20$ mV/K for CPTA).

A comparison of SiPM characteristics from different manufacturers is shown in Fig. 4. The photon detection efficiency for green light from the Y11 WLS fiber, gain, cross-talk, and noise rate are shown as a function of overvoltage for detectors produced by MEPhI/PULSAR (Russia), CPTA (Russia) (CPTA 143), Hamamatsu (Japan) (MPPC S10362-11-050C). For these measurements we used a calibrated light source which was being monitored with a standard PMT. To minimize statistical fluctuations, the data shown are averaged over 10-50 specimens from each vendor. While the breakdown voltage varies for individual specimens, the dependence on overvoltage ($\Delta V = V - V_{\text{break down}}$), in general, has a very small dispersion; $V_{\text{break down}}$ itself can be extrapolated assuming a linear gain dependence on voltage.

MEPhI/PULSAR SiPM’s have been developed much earlier than other mass produced SiPM’s, and their efficiency is considerably lower. SiPM’s produced by CPTA and Hamamatsu meet our minimum requirements, defined by high registration efficiency for Minimum Ionizing Particles (MIP) and low cross-talk. In spite of the higher observed one pixel noise for CPTA SiPM’s, their smaller cross-talk value results in a relatively low noise rate of the order of kHz at the 7.5 p.e. ($\sim 0.5$ MIP) threshold. In any case the noise rate is not critical for our system since at the chosen threshold the main background comes from neutrons, rather than SiPM noise. Both manufacturers have produced thousands of SiPM’s that matched to the 1.2mm diameter fiber. Both CPTA and Hamamatsu were considered as the primary SiPM vendors for the T2K experiment. Our choice between these two (otherwise acceptable) vendors is made based on the radiation hardness study as described in Section 3.2.

### 2.3 Scintillator strips

The largest light yield in the blue regime is achieved with organic scintillators, e.g. those produced by Bicron. However, the production technique for such scintillators does not allow to produce long strips without gluing together short strips and is very expensive to be practically considered for a detector having the area of the Belle II KLM system (> 1000 m²). Therefore, we have focused on achieving sufficient light yield with much cheaper polystyrene scintillators.

Scintillator strips made of polystyrene usually doped with PTP (1.5%) and POPOP (0.01%) can be produced by extrusion, allowing potentially very long strips. Although different vendors use slightly different ingredients and production techniques, they generally achieve quite similar quality
and set similar prices. We tested the characteristics of the scintillator strips from three vendors: “Amkris-Plast” (Kharkov, Ukraine), which produced the strips in use for the Opera experiment [8], Fermilab (USA), and “Uniplast” (Vladimir, Russia), which both produced the scintillator strips for the T2K experiment [9]. All strips had width 40 mm; the height of the Amkris-Plast and Fermilab strips was 10 mm. For the third vendor, we used the existing Uniplast strips produced for the T2K experiment with 7 mm thickness.

In all strips, Kuraray WLS Y-11(200)MSJ multi-clading 1.2 mm diameter fibers were glued using SL-1 gel produced at SUREL (St. Petersburg, Russia). The Kuraray fiber provides more light output than other fibers and also has a favorably long attenuation length. This fiber has been used in many detectors with similar geometry and scintillator plastic as under consideration here [6, 8, 9]. The light emission spectrum of the Kuraray Y11 fiber is, in fact, quite well-matched to the SiPM spectral efficiency.

The strips have been tested using a cosmic ray stand. The cosmic ray trigger is provided by

Figure 4. Overvoltage dependence of SiPM a) efficiency, b) gain, c) cross talk and d) noise frequency for photo-detectors from different manufacturers: Hamamatsu (triangles), CPTA (circles), MEPbl/PULSAR (squares).
a pair of short trigger strips \((L = 16 \text{ cm})\) placed above and below the strip under consideration. The trigger strips were moved along the tested strip to measure the light yield, as a function of the distance to the photodetector. All strips were tested using SiPM’s from the same vendor in order to minimize systematic errors. To determine the average number of detected photons, we correct the measured number of fired pixels by the known cross-talk fraction \(1/(1 + \delta) \sim 0.85\) and conservatively use a truncated mean of the Landau distribution, discarding 10\% of the lower portion of the distribution and 30\% of the higher portion and then taking the average of the resulting samples. The resulting averaged number is then corrected by a factor of 0.87 for oblique incidence of cosmic-ray muons determined using a toy Monte Carlo simulation.

The distribution of the average number of detected photons is shown in Fig. 5a). For comparison, the light yield of the Fine-Grained Detectors (FGD) of T2K experiment, collected from the Fermilab strips \((10 \times 10 \text{ mm}^2)\), is shown in Fig. 5b) \([13]\). As can be seen from the distributions, we achieve a slightly higher light yield in spite of four times larger strip width in our case (the

![Figure 5. Distribution of the average number of SiPM-detected photons as a function of the distance to the photodetector: a) our study b) FGD at T2K experiment [13]. c) relative ADC response (expected to be proportional to the light yield) for two neighboring strips.](image)
light yield is approximately $\propto 1/\sqrt{\text{width}}$). We attribute this significant improvement in the light collection efficiency to the larger diameter of the fiber (light yield $\propto d$) and the gluing of the fiber to the strip.

The Fermilab and Uni plast strips, which have the same price per unit weight provide almost the same light yield at the SiPM, despite the fact that the Uni plast strips are 30% thinner (the total light yield is expected to be $\propto \sqrt{\text{height}}$). Apart from considerations of cost and weight of the entire system, the smaller scintillator thickness is beneficial in terms of reducing the neutron background. Indeed, the neutron rate is proportional to the scintillator volume. This consideration motivated our selection of the Uni plast strips for the Belle II KLM construction.

The transverse uniformity of the strip response was measured using tightly collimated and triggered radioactive source. Figure 5 c) shows the relative ADC response, which is proportional to the light yield, for two strips mechanically pressed against each other. The nonuniformity of the response is $\pm 25\%$. Decreases in the number of registered photons are observed near the groove, where the effective thickness of the scintillator is smaller, and at the strip edge, where the efficiency for scintillator light to reach the WLS fiber is smaller. From these results, we conclude that the light yield is adequate, irrespective of where a particle hits the strip.

We measure the time resolution using the cosmic-ray trigger for a strip read-out by two SiPM's, one on each fiber end. A TDC was started by one SiPM signal and then stopped by the second. From the observed time difference distribution, we can derive a time resolution of $\sigma_t \approx 0.7\,\text{ns}$. The measured velocity of light propagation in the WLS Y11 Kuraray fiber with 1.2 mm diameter is $v = 17\,\text{cm/ns}$, which translates into $\sim 12\,\text{cm}$ of spatial resolution along the strip.

3. Longterm stability and radiation hardness

Scintillator counters with WLS fiber using standard PMT read-out are used in many existing detectors, including those at hadron colliders, where the radiation dose is a few orders of magnitude higher than those anticipated at SuperKEKB. Such counters typically operate without degradation for decades. For example, light collection for the electromagnetic calorimeter for the HERA-B experiment is based on Uni plast scintillator tiles read-out by Kuraray Y11 [16]. During six years of operation, no deterioration of the electromagnetic calorimeter performance was observed.

SiPM's demonstrate excellent longterm stability. Our experience in operating the 7620 channel CALICE hadron calorimeter prototype using scintillator/WLS fiber/SiPM detecting tiles during three-year beam tests at CERN and FNAL [11, 12] showed no significant deterioration of performance. Only 8 dead channels (0.1%) were observed, while the characteristics of the remaining channels were unchanged. The long-term stability of Hamamatsu SiPM’s was tested in the T2K experiment, where $\sim 65$ thousand channels were studied during more than one year of operation. Failure was observed in $\sim 20$ channels, i.e. less than 0.03%, primarily owing to mechanical damage.

However, the adequacy of SiPM’s radiation hardness for our application needs to be proven experimentally. In particular, the radiation hardness of SiPM’s was measured to be high in the case of irradiation with electrons and photons, while neutrons and protons cause significant damage at a moderate integrated dose of $\sim 1\,\text{kRad}$ [11, 17]. Typical radiation damage consists of defect formation in the thin area from which charge carriers are collected, resulting in an increase of the
SiPM noise rate and, consequently, the dark current. Overall, the SiPM dark current grows linearly with the particle flux as in other silicon detectors.

3.1 Study of scintillator strips aging

The longterm stability of the light collection efficiency of strips with glued WLS fibers was tested using a test module consisting of 96 strips (1 meter long), manufactured in 2006. The test module was used for measurement of the neutron background in the KEKB tunnel for a period of 6 months. Modules were placed in the ‘hot’ region and accumulated a dose corresponding roughly to 3-5 years of Belle II operation. In 2009, these strips were retrieved and examined for radiation damage and aging. No degradation of the light yields (using new, not irradiated SiPM’s) within the 10% accuracy of the measurements was observed three years after production. We also subjected a short strip with glued WLS fibers to fast aging in a thermostat at a temperature 80°C during 4 months and again found no noticeable aging effects.

3.2 SiPM’s aging

Given the relative novelty of SiPM’s, we have studied their radiation hardness in detail, including any possible deterioration as a function of particle type to which they are subjected. Radiation damage from proton and neutrons is energy-dependent and difficult to predict without knowledge of the beam background spectra. Therefore, to measure possible damage to SiPM’s due to the high radiation levels anticipated at SuperKEKB, we performed radiation tests directly in the KEKB tunnel. Eight SiPM’s produced by Hamamatsu and eight CPTA SiPM’s were placed for 6 weeks in the KEKB tunnel at a location where the dose is much higher than in the nominal SiPM position. The integrated neutron dose at the tunnel measured with Luxel badges (J-type) was $\sim 1.2\text{ Sv}$. After irradiation, the SiPM dark current increased for both Hamamatsu and CPTA devices by a factor of 3.6 with a small dispersion ($\sim 15\%$) in 8 specimens.

The neutron dose was also measured near the nominal in situ position of the SiPM. The measured dose varies from 0.8 to 2.0 mSv/week at a luminosity $\mathcal{L} \sim 2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$. Assuming conservatively that the neutron dose increases linearly with luminosity, the expected neutron dose integrated over 10 years of SuperKEKB operation at $\mathcal{L} \sim 8 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$ does not exceed 40 Sv$^1$. The extrapolated factor of dark current increase after 10 years of SuperKEKB is therefore $\sim 150$. In the case of the Hamamatsu SiPM’s, the expected dark current is $\sim 14\mu\text{A}$, In the case of the CPTA SiPM’s, the dark current becomes much higher ($\sim 200\mu\text{A}$), since the gain and the initial noise are higher for the CPTA SiPM’s. The difference between the Hamamatsu and CPTA SiPM’s can be explained by the different thickness of the sensitive zone and the difference in manufacturing details (purity of the raw materials and also of the SiPM surface) on which both the initial noise and the anticipated performance depend.

The study of SiPM properties after irradiation was done at the Institute of Theoretical and Experimental Physics (ITEP) in Moscow. The SiPM’s were subjected to fast irradiation in the 200MeV secondary proton beam of the ITEP synchrotron ($\sim 10^{10} \text{ p/cm}^2/\text{hour}$). One month after irradiation the Hamamatsu SiPM dark current was measured to be $16\mu\text{A}$ for two specimens sub-

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$^1$The Monte Carlo simulation of the radiation dose actually predicts a dose which varies less slowly than linearly.
jected to an integrated proton flux $2.0 \times 10^{11} \, p/cm^2$ and $6.5 \, \mu A$ for two specimens subjected to an integrated proton flux $7.4 \times 10^{10} \, p/cm^2$.

We studied the light yield from minimum-ionizing particles traversing the far end of the strip ($\sim 3$ m from the photodetector) detected with both non-irradiated and also irradiated SiPM’s. The average number of photoelectrons (p.e.) from the MIP signal using irradiated and control SiPM’s is unchanged, though in the case of irradiated SiPM’s, the MIP signal is slightly smeared owing to increased noise. The dependence of the efficiency at the far end of the strip and the noise rate on the threshold in terms of the number of photoelectrons is presented in Fig. 6. We conclude that the light detection efficiency is not significantly changed after irradiation, while the internal noise rate increases significantly. However, at a threshold of $\sim 7.5$ fired pixels the background rates from the increased SiPM noise remains smaller ($\lesssim 10 \, kHz$) than the physical background rate due to neutron hits in the scintillator ($\lesssim 160 \, kHz$ for the longest strip). The MIP detection efficiency is similar with irradiated CPTA’s SiPM, but the noise rate becomes unacceptably high ($100 – 500 \, kHz$).

![Figure 6](image_url)

**Figure 6.** Dependence on the threshold (defined by the number of photoelectrons) of a) the MIP detection efficiency from the strip far end and b) the internal noise rate for Hamamatsu SiPM. The triangles correspond to the non-irradiated SiPM; circles correspond to SiPM’s irradiated with a $7.4 \times 10^{10} \, p/cm^2$ dose (corresponding to 5 years of operation at SuperKEKB) and the squares show the case of an SiPM irradiated with $2.0 \times 10^{11} \, p/cm^2$ dose (more than 10 years of operation at SuperKEKB).

We therefore conclude that the Hamamatsu’s SiPM radiation hardness is sufficient for successful KLM operation at the design SuperKEKB luminosity for at least 10 years. The significantly increased dark current, however, should be considered in the design of electronics, HV supplies, slow control and the calibration procedure.

4. Physics Performance

Besides the main mission to detect $K^0_L$ mesons and muons, another important task for the KLM system at Belle II, motivated by our extensive Belle experience is to serve as an hadronic veto to
improve the signal to background ratio for the so-called missing energy modes, such as $B^+ \rightarrow \tau^+ \nu$, $B \rightarrow h \nu \bar{\nu}$, etc. Indeed, the major background remaining after baseline selection for these modes is due to $B$-decays with missing neutrals or un-reconstructed charged hadrons. In this case, a veto on KLM hadronic clusters would be very useful, provided a high efficiency and low background can be achieved with the new KLM system.

The muon identification and hadron cluster reconstruction performance depends on the background rate, mostly related to slow neutrons produced in the accelerator tunnel and in the vicinity of the interaction region. In spite of the much higher sensitivity to neutrons of scintillators containing hydrogen compared to the gas+glass based RPC, the total background rate of the proposed KLM system is expected to be much lower than those achievable with RPC design. Indeed, single background neutrons are usually absorbed in one scintillator strip, so there are no two-dimensional hits from single background particles; fake two-dimensional hits mostly arise from random coincidences within the integration time. This is in contrast to RPC, where even a single scattered neutron can induce signals on both stereo strips.

To estimate the background rate we have used two independent methods: i) a conservative extrapolation of the measured neutron rates taken with scintillator test module, and ii) a Monte Carlo detector study.

4.1 Measurement of the background neutron rate

As RPC and scintillators have different responses to beam backgrounds, an extrapolation of the known Belle background rate at the RPC to the expected rate at the scintillator KLM at SuperKEKB is difficult. We have therefore performed measurements of the neutron flux using a scintillator KLM test module installed directly in the KEKB tunnel close to the KLM endcap. The test module contained four layers. Each layer, surrounded by a shielding box for protection from external light, was assembled from 24 strips. Each scintillator strip with a WLS fiber and SiPM readout had a size of $1000 \times 40 \times 10$ mm$^3$. During KEKB operation the signals from 96 channels were collected by random triggers using CAMAC ADC’s, with trigger gate set to be 100 ns.

We found that a simple shielding box was inadequate for protecting the module from numerous charged tracks and showers. To discriminate neutron signals from other sources, different hit patterns in the four layers were used. A significant portion of the observed events (where at least one SiPM signal exceeds the threshold of 0.5 MIP) had multiple hits from charged tracks or showers; to suppress such backgrounds, we required a veto in the two outer layers and also required a single hit in one of the two inner layers. The calculated neutron rate at a nominal 0.5 MIP threshold, at a luminosity of $\mathcal{L} \sim 1.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$, was 6 Hz/cm$^2$. We use this number to estimate the occupancies in the readout electronics and trigger (maximum 160 kHz from the longest strip, 60 kHz averaged), as well as to estimate the expected backgrounds for $K_L^0$ reconstruction.

4.2 Monte Carlo simulation

The proposed endcap KLM detector geometry is coded into the GEANT4 package, which then simulates the energy deposition of signal hits in each strip. Both signal events and neutron backgrounds were simulated in this way. For the neutron background a $\pm 6$ m accelerator tunnel side was simulated, including a realistic description of the SuperKEKB optics and also including radiative Bhabhas, the Touschek effect and other background sources. The response of the KLM system
on the energy deposition is simulated based on our test measurements. We assume that multiple
hits at the same strip are correctly resolved by the readout electronics if their arrival time difference
is greater than 10 ns, otherwise they are merged into one hit. Hit information is stored for further
analysis if the amplitude exceeds the threshold of 7.5 p.e.

The background induced by neutrons turned out to be slightly lower than those obtained
from our conservative extrapolation described above, corresponding to a maximum 120 kHz for
the longest strip. For the background studies, we assume that hits are distributed uniformly in time.
We use similar procedures to digitize both background and signal hits.

4.3 Superlayer cluster reconstruction

The KLM hit reconstruction procedure is similar to that used in the Belle reconstruction software.
We exploit the improved time resolution that can be achieved with the new electronics and DAQ.

Neighboring hit strips in the same plane with hit time difference smaller than 10 ns are grouped
to form a 1D hit with coordinate defined as the weighted average over the hit-strips’ coordinates.
Two 1D hits from orthogonal layers in the same superlayer that intersect spatially and match in
time form a ‘2D hit’. The reconstructed 2D hits from all superlayers are used for muon and $K_L^0$
reconstruction.

4.3.1 Muon identification

The muon identification procedure, for muons exceeding the detection threshold of 0.6 GeV/c is
based on the extrapolation of reconstructed charged tracks outward from the Belle II drift chamber
into the KLM detector. The muon identification procedure then compares the likelihoods of muon
and hadron hypotheses based on the longitudinal and transverse profiles of the extrapolated tracks
to KLM 2D hits within some geometric matching requirement.

Misidentification is mainly due to hadronic showers and pion or kaon decay in flight, which is
thus largely independent of the KLM detection technique. However, the expected efficiency of the
scintillator KLM detector is slightly higher than for the current Belle KLM; we therefore expect
that the muon identification performance should be slightly improved.

The measured muon detection efficiency and pion fake rate are approximately constant for mo-
menta greater than 1.0 and 1.5 GeV/c, respectively. Between 1.0 and 3.0 GeV/c the averaged muon
detection efficiency is 90% and the hadron fake rate is less than 1.5% over the KLM acceptance,
using the standard likelihood selection criterion $\mathcal{L}^0 > 0.9$.

4.3.2 $K_L^0$ reconstruction

Following the procedure used at the Belle experiment, $K_L^0$ clusters are reconstructed as a group of
2D hits within a 5$^\circ$ cone angle relative to the interaction point, which are compatible in time with
being produced by a single nuclear shower. As in the present algorithm we require 2D hits in at
least two superlayers. The efficiency for $K_L^0$ cluster-finding in the KLM is shown in Fig. 7(a)
as a function of $K_L^0$ momentum. The angular resolution is $\sim$ 10 mrad over a wide momentum range,
which is approximately the same as for the Belle system.

The main source of $K_L^0$ fake candidates is the random coincidence of 1D hits induced by neu-
trons. After SiPM irradiation, some small contribution to fake candidates arises from the increased
SiPM noise. We find $\ll 0.01$ fake $K_L^0$ candidates per event at the designed luminosity. Given that the fake rate is negligibly small, we have studied the possibility to increase the $K_L^0$ efficiency by releasing the cluster selection, allowing 2D hits in only one superlayer. This results in an increased $K_L^0$ efficiency by up to 30% (Fig. 7a, open squares), while maintaining the background rate at a relatively low level ($<0.2$ fake cluster/event). Further fake cluster rate suppression can exploit both amplitude information, as well as the one-superlayer hit pattern characteristics, depending on the signal-to-noise requirements of a particular analysis.

We may also take an advantage of the excellent scintillator time resolution to determine the $K_L^0$ momentum using the KLM system as time-of-flight detector, at least for medium-momentum kaons. The obtained momentum resolution as a function of $K_L^0$ momentum is shown in Fig. 7b. The timing measurements provide useful information for kaons with momenta up to 1.5 GeV/c.

Based on the simulation we conclude that the proposed detector provides even better performance for $K_L^0$ reconstruction than the present one, and thus also an improved hadronic veto for the study of the important $B$ decays modes with neutrinos in the final state.

5. Conclusion

We have studied the KLM system based on scintillator counters with WLS fiber light collection and SiPM readout for the Belle II experiment. The proposed system should work efficiently at background rates and radiation doses $\sim 100$ times larger than those observed for the Belle experiment. As demonstrated by many tests described herein, the system has sufficient robustness to operate smoothly in a strong magnetic field and high radiation and interaction environment with no significant degradation anticipated after many years of data-taking.
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