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

T. Aushev [a,b,c], D.Z. Besson [a,d,*], K. Chilikin [a,b], R. Chistov [a,b], M. Danilov [a,b], P. Katrenko [a,b], R. Mizuk [a,b], G. Pakhlova [a,b], P. Pakhlov [a,b], V. Rusinov [a,b], E. Solovieva [a,b], E. Tarkovsky [a,b], I. Tikhomirov [a,b], T. Uglov [a,b,c]

[a] National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoye shosse 31, Moscow 115409, Russia
[b] Institute for Theoretical and Experimental Physics, B. Cheremushkinskaya 25, Moscow 117218, Russia
[c] Moscow Institute of Physics and Technology, Institutskiy per. 9, Dolgoprudny, Moscow Region 141700, Russia
[d] University of Kansas, Department of Physics and Astronomy, 1082 Malott Hall, Lawrence, KS 66045, USA

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ABSTRACT

A new K_L^0 and muon detector based on scintillators will be used for the endcap 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 wavelength 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.

1. Overview

Over the last decade, the B-factory experiments, Belle and BaBar, have shown 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 $8\times10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Currently the SuperKEKB Factory, and the associated Belle II subdetectors are under construction at the High Energy Accelerator Research Organization, KEK, in Tsukuba, Japan. This new installation is expected to begin operation at the end of 2015 with the goal of collecting an integrated luminosity of $50\,\mathrm{ab}^{-1}$ by 2020.

The K_L^0 and muon subsystems (KLM) in the Belle experiment were designed to detect K_L^0 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 sections. The RPC KLM detector operated successfully over the entire lifetime of Belle (1999–2010). However, the endcap KLM gas detectors of the Belle II experiment would 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 endcap KLM (EKLM) detector and demonstrate that it matches the scientific and environmental requirements. The prospects for this technology were first discussed in a previous paper [5], after which this technology was chosen as the baseline technology for Belle II. Considerable R&D studies have been performed in order to demonstrate the feasibility of the proposed approach, and the construction of the new EKLM detector is already underway. A similar approach was also proposed for the SuperB experiment in Italy [6], which has since, quite unfortunately, been terminated.

2. The Belle II EKLM system

The Belle II EKLM system will follow its Belle predecessor, consisting of alternating layers of active charged particle detectors

* Corresponding author.
E-mail address: zedlam@ku.edu (D.Z. Besson).

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and 4.7 cm thick iron plates. The iron plates serve as the magnetic flux return for the solenoid and provide a total of 3.9 interaction lengths of material for a particle travelling normal to the detector planes. There are 14 detector and 15 iron layers in each of the forward and backward endcaps. Each detector layer is divided into 4 sectors, which can be separately installed. Since the Belle iron structure will be retained, we plan to simply swap in our new detector, subject to the constraint that it must mate with the existing sector frames which guide installation into the 4.0 cm wide iron gaps.

Scintillator counters with wave-length-shifting (WLS) fibers as a readout option for the EKLM were first proposed by our group in the Belle upgrade Letter of Intent [1]. Charged particle detection with such detectors, 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 the strong magnetic field do not allow use of PMTs. As an alternative photodetector, we proposed multipixel silicon photodiodes operating in the Geiger mode, originally developed in Russia [9] in the 1990s, and currently produced by many companies under different names: Silicon PhotoMultiplier (SiPM), Avalanche Photo-Diodes (APD), Metal-Resistor-Semiconductor (MRS), Multi-Pixel Photon Counters (MPPC), Multi-Pixel Avalanche Photo-Diodes (MAPD), among others. In this paper, we will use the generic name SiPM to include all such detectors.

SiPMs allow for compact detectors and uncompromised operation in strong magnetic fields. The first large-scale (7620 channels) SiPM application was the CALICE experiment's hadron calorimeter [10,11], which demonstrated the feasibility to use SiPMs experimentally, as well as their advantages over traditional PMTs. The use of SiPMs in a real experiment with a huge number of readout channels (~65 k) began with the near detector of the T2K experiment [12], where many subsystems are based on SiPM readout of scintillator light. However, the background rates and the radiation environment in neutrino experiments are much more benign, and therefore more stringent testing is required to prove the applicability of this technique to the more exacting Belle II environment.

2.1. General layout

The base element of the new 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 2.8 m to match the geometry of an individual sector. The strip height is limited to 10 mm by the mechanical constraints of the gap between the iron yoke and the frame structure. The selected strip width of 40 mm is a compromise between the desire for a moderate number of channels and the required spatial resolution for muon and K_L^0 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 does not improve muon identification performance and K_L^0 angular resolution. The hit registration efficiency does not depend on the strip width as long as the rates remain below data acquisition (DAQ) and SiPM saturation levels.

A 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 (near) 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 optical glue. The SiPM is then coupled to the fiber end, and fixed and aligned with the fiber using a plastic housing.

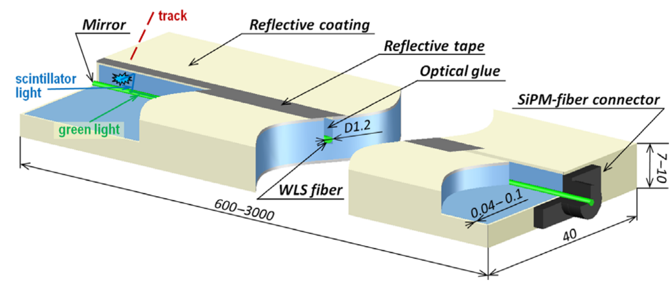

Fig. 1. Schematic view of the scintillator strip. Dimensions are in mm.

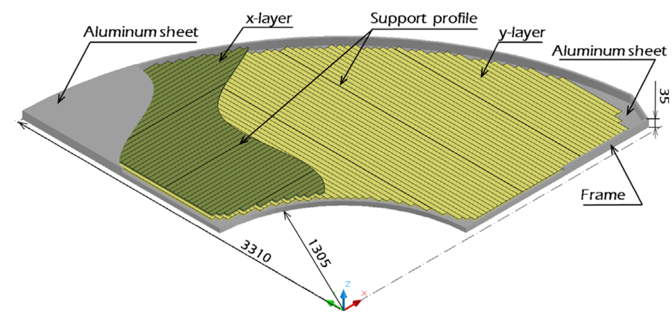

Fig. 2. Schematic view of one superlayer formed by scintillator strips. Sizes are given in mm.

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. Fifteen 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 prevents correlated hits in two layers appearing from a single background neutron. The sector frame is the same as that used for Belle's RPC mounting. The dead zone around the inner arc is estimated to be ~1% of the total sector area due to the inscription of the rectangular structure into the circular housing; this inner dead zone is approximately the same as that of the Belle RPC EKLM detector. Around the outer circumference, the dead zone is 4%, primarily owing to the presence of front-end electronics and cables. In practice, this dead area cannot be recovered, as the extremely short strips that might be installed there have very small coverage, and do not justify the additional number of readout channels they would entail.[1] 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 new system is slightly better than that of the Belle RPC EKLM.

In the new EKLM system the scintillator-based superlayers are installed in all 14 gaps in the magnet yoke in both the forward and backward endcaps. The entire system consists of 16,800 scintillator strips of varying lengths.

[1] We note that the acceptance loss at large radii is not critical for muon and K_L^0 reconstruction.