The $K_L/\mu$ Detector Subsystem for the BELLE Experiment at the KEK B-factory

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23 August 1999

Abstract

The $K_L$ and muon detection subsystem of the BELLE experiment at the KEK-B asymmetric B-factory is described. The system consists of resistive plate counter charged particle detectors installed within the segmented flux return iron of the BELLE superconducting solenoid. The design and construction of the detectors, including the gas distribution system and readout electronics, are described in detail. The operating characteristics and performance of the glass electrode RPCs with cosmic rays and $e^+e^-$ collision data are presented.

Preprint submitted to Elsevier Preprint 23 August 1999
1 Introduction

The BELLE detector is designed to measure the properties of the particles produced in the collisions of electrons and positrons at the KEK-B asymmetric B-factory at the Japanese Institute of Particle and Nuclear Studies[1]. The primary physics goals of this experiment are the measurement of CP-violation parameters involving beauty quarks[2]. Many of the measurements require the identification of muons from the semileptonic decay of B and D mesons and from $J/\psi \rightarrow \mu^+\mu^-$. The decay process $B^0 \rightarrow J/\psi K_L$ can be used to measure the CP violation parameter $\phi_1$ which is one of the unitarity triangle angles in the CKM quark mixing matrix of the standard model of elementary particle physics [3]. With these physics goals in mind the $K_L/\mu$ subsystem was designed to identify $K_L$ 's and muons with high efficiency over a broad momentum range greater than 600 MeV/c. The barrel-shaped region around the interaction point covers an angular range from 45° to 125° in polar angle and endcaps in the forward and backward directions extend this range to 20° and 155°.

The $K_L/\mu$ system consists of alternating layers of charged particle detectors and 4.7cm thick iron plates. There are 15 detector layers and 14 iron layers in the octagonal barrel region and 14 detector layers and 14 iron layers in each of the endcaps. The iron plates provide a total of 3.9 interaction lengths of material for a particle travelling normal to the detector planes. In addition, the electromagnetic calorimeter (CsI) provides another 0.8 interaction lengths of material to convert $K_L$ 's. Figure 1 shows the BELLE detector with the segmented magnetic flux return iron in the barrel and endcap regions. The $K_L$ particles which interact in the iron or CsI produce a shower of ionizing particles. Measuring the direction of these $K_L$ showers allows one to reconstruct decays such as $B^0 \rightarrow J/\psi K_L$ using the kinematic constraints of energy and momentum conservation. The multiple layers of charged particle detectors and iron allow discrimination between muons and charged hadrons based upon the distance that they travel and the amount of scattering that occurs. Weakly interacting muons travel significantly farther with smaller deflections on average than strongly interacting hadrons.

The charged particle detection is provided by glass electrode resistive plate counters (RPCs)[4-8]. Glass RPCs have a long history dating back to the early 1970's [9], but this is the first experiment in which large area glass detectors operated at atmospheric pressure have been used. Resistive plate counters
have two parallel plate electrodes with high bulk resistivity (> $10^{10}$ Ω-cm). When an ionizing particle traverses the gap it initiates a local discharge of the plates which is limited by the high resistivity of the plates and the quenching characteristics of the gas between the plates. The discharge induces a signal on external pickup strips, which can be used to record the location and the time of the ionization.

The details of the barrel and endcap module design and construction are described in section 2. The gas mixing and distribution system with pressure control, which is vital to the successful stable operation of these glass detectors is described in section 3. In section 4 we describe the readout electronics which uses time multiplexing to reduce the number of electronics channels. Finally, the operating characteristics of the RPCs themselves and their performance in the BELLE experiment detecting $K_L$ ’s and muons are presented in section 5.
2 Construction

2.1 RPC Superlayers

There are minor differences between the barrel modules, which were built in the United States, and the endcap modules which were built in Japan. The barrel glass electrode resistive plate counters consist of two parallel sheets of 2.4 mm thick commercially available float glass (73% silicon dioxide 14% sodium oxide 9% calcium oxide and 4% trace elements). The glass used in the endcap RPCs is 2.0 mm thick. The bulk resistivity of the glass is $\sim 5 \times 10^{12} \, \Omega \text{cm}$ at room temperature. The plates are separated by 1.9mm thick noryl spacers epoxied in place. Long spacers with a cross section shown in figure 2 were epoxied every 10 cm inside the barrel RPCs and a t-shaped noryl spacer was epoxied around the perimeter forming a gas tight unit. The epoxy used in the barrel RPCs was 3M 2216. In the endcap RPCs 3M DP460 epoxy was used. The spacers were designed with concave regions for the epoxy joints and were extruded to an accuracy of $\pm 0.05 \, \text{mm}$. The high voltage is applied to the outer surface via a coat of Koh-i-noor 3080F india ink for the barrel modules. The ink was mixed 30% black and 70% white by weight to achieve a surface resistivity of $\sim 1 \, M\Omega/\text{square}$. This resistivity is chosen so that this surface does not shield the discharge signal from the external pickup pads but is small compared to the resistivity of the glass to provide a uniform potential across the entire surface. A conducting carbon tape SHINTRON STR-9140 with a surface resistivity of $10^7 - 10^8 \, \Omega/\text{square}$ was applied to the outer surface of the endcap RPCs.

Fig. 2. Internal spacer and edge spacer cross sections.

Internal Spacer       Edge Spacer
1.90+/-0.05mm
A schematic diagram of an endcap RPC is shown in figure 3. The spacers were placed in such a way that they channel the gas flow through the RPC to provide uniform gas composition throughout the active volume.

The barrel RPCs are similar but rectangular in shape and vary in size from $2.2 \times 1.5$ M$^2$ to $2.2 \times 2.7$ m$^2$. Tilting table tops were used to lift the RPCs into a vertical orientation to avoid flexing the epoxy joints. After assembly the RPCs were always moved in a vertical orientation or supported by a rigid flat surface. Approximately 18 barrel superlayers weighing an average of 110 kg each were crated with 8 cm of rigid foam packing material surrounding them. They travelled by land and sea from the United States to Japan. The glass RPCs are relatively robust except for overpressure situations which can push the two sheets of glass apart breaking the spacer-epoxy joint.

To avoid the danger of atmospheric pressure changes creating overpressure situations the gas volume was not sealed during shipping. Relief bubblers protect the RPCs during operation. Many of the modules in the first crate shipped were found to have the glass separated from the internal spacers. After changing the proximity of the spacers from 15cm to 10cm and increasing the amount of epoxy on the spacers we had no more separations of glass from internal spacers. Subsequent shipments were found to be quite robust and survived shipment and installation with only 5 RPCs developing leaks in transit. The endcap RPCs were built at Tohoku University and trucked to KEK without incident.

Each RPC is electrically insulated with a double layer of 0.125 mm thick mylar. Signals from both RPCs are picked up by copper strips above and below the pair of RPCs providing a three-dimensional space point for particle tracking. Multiple scattering of particles as they travel through the iron is typically a few centimeters. This sets the scale for the desired spatial resolution of the $K_L/\mu$ system. The pickup strips in the barrel vary in width from layer to layer but are approximately 50mm wide with lengths from 1.5 to 2.7 m. The endcap $\theta$ strips are 36 mm wide and vary in length from 2 to 5 m. The endcap $\phi$ strips are 1.83 m long and vary in width from 19 mm to 47 mm. The geometry of the pickup strips was chosen so that the pickup strips behave as a transmission line with a characteristic impedance of $\sim 50\Omega$ to minimize signal reflections within the superlayer.

The crosssection of a superlayer in figure 4 shows the two RPCs sandwiched between orthogonal pickup strips with ground planes for signal reference and
proper impedance. This two-RPC and two-readout-plane sandwich is enclosed in an aluminum box and is less than 3.7 cm thick. The double-gap design provides redundancy and results in high (≥ 98%) superlayer efficiency, despite the relatively low (90% to 95%) single-layer RPC efficiency. In particular, the effects of dead regions near the spacers are minimized by offsetting their locations for the two RPCs that comprise a superlayer. To provide overall operational redundancy, care is taken to supply gas and HV for each RPC layer so that the superlayer can continue to operate even if a problem develops with one RPC.

The $K_{L}/\mu$ subsystem covers a total area of 2200$m^{2}$ and consists of 240 superlayer modules in the barrel region and 112 superlayer modules in the endcaps. Each barrel module has two rectangular RPCs with 48 $z$ pickup strips perpendicular to the beam direction. The smaller 7 superlayers closest to the interaction point have 36 $\phi$ strips and the outer 8 layers have 48 $\phi$ strips orthogonal to the $z$ strips. Each endcap superlayer module contains 10 pie-shaped RPCs as shown in Figure 3. Figure 5 shows an endcap superlayer module cutaway view with the 96 $\phi$ and 48 $\theta$ pickup strips in each module. There is a total of 38k pickup strips in the $K_{L}/\mu$ system. A detailed description of the readout electronics is given below in section 4.
2.2 High Voltage System

During data taking the modules typically operate with a total gap voltage of 8 kV. Rather than grounding one electrode and using a single-ended supply to bias the other, we chose to separately apply positive voltage to the anodes and negative voltage to the cathodes. This approach minimizes the potential
to ground on connectors, cables, and surfaces as a precaution against external discharges through and around insulators. Moreover, it helps reduce the overall HV system cost since modules capable of producing voltages in excess of 7.5 kV are less common and therefore more costly.

We are using the LeCroy VISyN high voltage system, which consists of Model 1458 mainframes and plug-in modules (the Model 1468P for the anodes and the Model 1469N for the cathodes). The cathodes are set at -3.5 kV and the anodes are set at +4.7 kV for the barrel RPCs and +4.5 kV for the endcap RPCs. To reduce the number of high voltage channels the anode planes are ganged together and controlled by one positive high voltage channel. In the barrel eight anode planes are ganged together and in the endcaps five anode planes are ganged together. The total current drawn by the RPCs during operation is approximately 5 mA or \( \sim 1 \mu \text{A/m}^2 \) of RPC area. For properly operating chambers, most of this current flows through the noryl spacers.

3 Gas

3.1 Mixture

We have investigated gas mixtures in search of an environmentally friendly and non-combustible mixture that provides high detection efficiency and stable RPC operation [16]. The gas we have chosen consists of a non-combustible mixture of 62% HFC-134a, 30% argon, and 8% butane-silver. Table 1 lists some basic physical parameters of these gases. Butane-silver is a mixture of approximately 70% \( n \)-butane and 30% \( iso \)-butane roughly.

The average density of this mixture is

\[
0.62 \times 4.5 + 0.30 \times 1.78 + 0.08 \times 2.6 = 3.532 \text{g/l} \tag{1}
\]

There are two separate banks of bottles for each type of gas. When one side becomes empty the supply line automatically switches to the other. Tank quantities are measured by weight for butane and HFC-134a and by pressure for argon. A diagram of the mixing system is shown in figure 6. The three gases are sent to MKS model 1179A mass flow controllers for mixing in the
<table>
<thead>
<tr>
<th>Gas</th>
<th>Symbol</th>
<th>mol. weight</th>
<th>density</th>
</tr>
</thead>
<tbody>
<tr>
<td>argon</td>
<td>$Ar$</td>
<td>39.95</td>
<td>1.784 g/l (0 deg C, 1 atm)</td>
</tr>
<tr>
<td>butane-silver</td>
<td>$C_4H_{10}$</td>
<td>58.12</td>
<td>2.6 g/l (0 deg C, 1 atm)</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>$CH_2FCF_3$</td>
<td>102.0</td>
<td>4.5 g/l</td>
</tr>
</tbody>
</table>

Table 1

![Diagram](https://via.placeholder.com/150)

**Fig. 6. The gas mixing system.**

appropriate ratios. There are four gas mixing systems; one for the inner RPCs in the barrel superlayers, one for the barrel outer RPCs, one for endcap inner RPCs, and one for endcap outer RPCs. During normal operation we flow a total of 4.5 l/min which corresponds to approximately one volume change per day.
3.2 Distribution System

A diagram of the $K_T/\mu$ gas distribution system is given in Figure 7. The gas distribution system is designed to provide an independent gas supply to each RPC in a superlayer so that if one supply line fails for any reason the other RPC in the superlayer will still be operational. Mixed gas is distributed to 704 individual RPC layers through a series of manifolds. To insure uniform distribution of the flow without the need for tedious adjustments, a “flow resistor,” was inserted in series upstream of each RPC. These devices are 10-cm-long stainless-steel tubes with an inner diameter of 254 $\mu$m. The flow impedance of the tubes is about ten times larger than that of an RPC layer. The flow rate from the manifolds is then determined by the flow resistor (uniform to about 10%) and largely independent of variations in the flow resistance of individual RPCs.

Fig. 7. The gas distribution system.

The exhaust system is shown in figure 8. Tests showed that the epoxy joints between the glass plates and the internal spacers begin to detach when a
barrel RPC is pressurized above 50 mmAq. When this happens the RPC is still gas tight, but detector performance begins to deteriorate because the gap in the mid-region becomes larger than the nominal value. When more than 150 mmAq pressure is applied the epoxy joints between the glass plates and the edge-spacer begin to fail and a gas leak develops. Active control of the exhaust pressure and relief bubblers at various points in the system were introduced to avoid these overpressure situations.

For reasons of safety, the gas cannot be exhausted in the experimental hall. The exhaust gas from each channel goes through a bubbler to a common manifold, and then is taken out of the experimental hall through a 20-m vertical exhaust line. Since the average density of the mixed gas is significantly larger than that of air (3.53 g/l compared with 1.3 g/l for air), the gas volume that fills the exhaust line corresponds to about 40 mmAq pressure at the level of the RPCs. We reduce this pressure differential to nearly zero by using a venturi pump and pressure-regulated buffer volumes in the exhaust lines. The venturi pump provides a constant suction that is somewhat larger than what is needed to pump the gas to the surface. A feedback loop consisting of a
differential pressure transducer (Baratron #223B), an electronic control unit (MKS #250), and a variable-impedance proportional solenoid valve (MKS Model #248) adjusts the exhaust impedance to maintain the exhaust buffers at the desired value.

4 Readout Electronics

Readout of 38k pickup strips is accomplished with the use of custom-made VME based discriminator/time-multiplexing boards developed by Princeton and Osaka City Universities. The system consists of the signal discrimination and multiplexing boards, crate controller boards (one per crate) for crate-wide control and data processing, string controller boards for downloading and controlling multiple readout crates, and Fastbus time-to-digital converters.

The discriminator boards are 6U size VME boards with 96 input channels per board. A comparator (MAX908CPD) is used to generate a logic signal if the voltage on the input channel exceeds the threshold voltage. This threshold can be selected via a programmable digital-to-analog converter to be any value from -250mV to +250mV. A time multiplexer scheme combines hit information from 12 RPC channels into a single high-speed serial data stream that is passed to a LeCroy 1877 pipelined time-to-digital converter (TDC). The multiplexing is accomplished with the use of a Xilinx XC4005E field programmable gate array (FPGA). A schematic diagram of the readout electronics is shown in figure 9. In addition, the logical OR of the hits for each 12-channel group is generated and is available for use as a fast trigger signal.

Each $K_L/\mu$ VME crate has a crate controller board which transmits control data from the string controller to the discriminator boards via the VME backplane. A 10MHz clock signal from the crate controller board is distributed throughout the crate for use by the discriminator boards in time sequencing the RPC hits. The string controller is a multifunction VME compatible board using a Xilinx 4013 programmable gate array to allow downloading and control of a string of up to 8 RPC readout crates. Once the discriminator board is programmed the time sequenced hit information travels directly from each 96 channel board to 8 TDC channels residing in a Fastbus crate. In this manner 38k RPC channels are reduced to 3200 Fastbus TDC channels resulting in a significant cost savings. It is also possible to read RPC strip-hit data directly
through the string controllers, as was done during system commissioning, when the production TDC system was not yet available.

5 Performance

5.1 Glass Electrode Resistive Plate Counters

In this section we describe the general characteristics of the glass electrode RPCs[13]. The relatively high resistance of the glass, $\sim 5 \times 10^{12} \, \Omega \, \text{cm}$, limits the rate capability of these counters to $\sim 0.2 \, \text{Hz/cm}^2$, but in this application where the particle flux is little more than the cosmic ray flux, the detectors function with high efficiency. We operate the barrel modules at 4.3kV/mm with a signal threshold of 40mV and the endcap modules at 4.2kV/mm with a signal threshold of 70mV. The choice of different operating points is due to the differences in the characteristics of the pickup strips for the barrel and the endcap. For example, the barrel modules have a 100$\Omega$ resistor connecting the pickup strip to ground at the cable end of the pickup strip to create an effective 50$\Omega$ impedance at that point. This reduces the size of the signal which reaches the readout boards for the barrel modules by a factor of two.
Figure 10 shows the efficiency versus voltage for each of the RPC planes in an endcap superlayer. These data were obtained using cosmic rays which penetrate the endcap. The efficiency is obtained by triggering on and tracking a particle using the other superlayers, calculating the expected location of the track as it passed through this superlayer, and looking to see if a hit was recorded at that location (±1 strip). The efficiency is then the ratio of the number of hits found to the number expected. In figure 11 an efficiency map with a grid determined by the readout strips is shown. With only one RPC layer active the RPC edges which are inactive are clearly seen. The area near the internal spacers, which are 2mm wide, is inactive. Care was taken to insure that the internal spacers in the two layers do not overlap. With both planes active, which is the normal operating condition, the superlayer acts as a logical “OR” for hits in either RPC layer and has an average efficiency that is typically over 98%.

Cosmic rays were used to map the efficiency and to determine the relative positions of all of the superlayer modules. Additionally, the response of the modules to penetrating muons was measured and the results were used as input to the simulation programs. For example, for a given operating voltage and discriminator threshold, a penetrating muon generates hits on an average of 1.4 strips per layer in the barrel modules and 1.9 strips per layer in the endcap modules. The spatial resolution of the modules is shown in figure 12.

This residual distribution is the difference between the measured and predicted hit location using a track that has been fitted using hits in the adjacent layers. The multiplicity refered to is the number of strips in the superlayer that have “signals over threshold. The TDCs provide time information for the hits which can be used to eliminate hits which are out of time with respect to the $e^+e^-$ collision. The time resolution of the $K_L/\mu$ system is a few ns. When multiple adjacent strips have signals over threshold the hit location is calculated by averaging the strips together. The standard deviation of this residual distribution is < 2 cm and gives angular resolution from the interaction point of better than 10 mrad.

5.2 Operating Experience

The system has been operating for approximately one year. When we first installed the modules we used 1/4 inch diameter flexible polyolefin tubing from
Fig.10-a. Efficiency plateau for 5 RPCs of top layer.

Fig.10-b. Efficiency plateau for 5 RPCs of bottom-layer.

Fig.10-c. Efficiency plateau for top, bottom, superlayer.

Fig.11-a. Efficiency map of top layer in endcap quadrant.

Fig.11-b. Efficiency map of bottom layer in endcap quadrant.

Fig.11-c. Efficiency map of superlayer in endcap quadrant.
Fig. 12 Spatial resolution of a superlayer.

the gas distribution manifolds to the RPCs. After several weeks of operation we noticed an increase in the dark current drawn by some of the RPCs and a corresponding decrease in efficiency. This was found to be due to water vapor in the air migrating through the tubing and entering the RPC active volume. Some of these tubes were as long as 12 meters and we measured concentrations of H₂O as high as 2000 parts per million in some RPC exhaust lines. Approximately 50% of the barrel modules were affected. The efficiency of some barrel RPCs dropped below 50% before corrective measures were taken. We replaced the plastic tubing with copper tubing to prevent additional water vapor entering the RPCs. The contaminated RPCs eventually dried out and have recovered most of their lost efficiency.

Two barrel RPCs have developed HV problems during the first year of operation. One has a short to ground and the other has an open such that HV is not getting to the electrode. The overall impact on system performance is small because of the redundancy of the double gap design. Figures 13 and
Fig. 13 Barrel superlayer efficiencies

Fig. 14 Endcap superlayer efficiencies

14 show the superlayer efficiencies for the 240 barrel superlayers and the 112 endcap superlayers respectively. Other than the initial water vapor problem, which has been solved, the RPCs have operated reliably and with an average efficiency of better than 97%.
In this section we present results obtained with $e^+e^-$ collider data taken during the summer 1999 commissioning run of the KEK B-factory. The identification of $K_L$ particles involves first associating hits in the $K_L/\mu$ system into clusters. Charged particles are measured in the inner tracking chambers and extrapolated into the $K_L/\mu$ system. Clusters within 15 degrees of an extrapolated charged particle are excluded as $K_L$ cluster candidates. For isolated clusters the center of gravity of the hits is calculated and used to determine the direction of the cluster from the interaction point. In Figure 15 we show a histogram of the difference between the $K_L$ cluster candidate direction and the missing momentum vector direction. The missing momentum vector is calculated using all of the measured particles in the event.

![Histogram of $d\eta$](image)

**Fig. 15** Difference between the neutral cluster direction and the missing momentum direction.

This histogram shows a clear peak where the neutral cluster measured in the $K_L/\mu$ is consistent with the missing momentum in the event. The number of neutral clusters per event is shown in figure 16 compared to a Monte Carlo simulation of the predicted number of $K_L$ clusters per event. The agreement with the prediction gives us confidence that the detector and our reconstruction software are performing correctly.
Fig. 16 Number of neutral clusters per event.

5.4 Muon detection

We have used penetrating cosmic rays, which are primarily muons, as a calibration tool to measure the superlayer efficiency and resolution. With the BELLE solenoid and central drift chamber measuring the cosmic ray momentum we can plot the detection efficiency as a function of particle momentum. Below 500 MeV/c the muon does not reach the $K_L/\mu$ detectors. A comparison of the measured range of the particle to the predicted range for a muon of that momentum in conjunction with the amount of scatter of the particle as it passes through the multiple layers of iron allows us to assign a likelihood to its being a muon. In Figure 17 the muon detection efficiency versus momentum is shown for a likelihood cut of 0.8. Some fraction of charged pions and kaons will be misidentified as muons. In the $e^+e^-$ collision data we have a sample of $K_S \rightarrow \pi^+\pi^-$ which we have used to measure this fake rate. The fraction of pions which are misidentified as muons is shown in Figure 18 again with a muon likelihood cut of 0.8. The histogram is a Monte Carlo simulation to be compared with the measurement. Above 1 GeV/c we have a muon identification efficiency of better than 90% with a fake rate of less than 5%.
Fig. 17 Muon detection efficiency versus momentum

Fig. 18 Fake rate versus momentum

6 Summary

We have built and operated a 2200m² K_L/µ particle detector for the BELLE experiment at KEKB using glass electrode resistive plate counters. Three gases
are mixed and distributed to 704 RPC layers with pressure control to prevent overpressurization of the detectors. A discriminator/time multiplexing VME based readout system using field-programmable gate arrays reduces the number of time-to-digital converters by a factor of 12 significantly reducing the instrumentation costs. The detectors have ~ 98% detection efficiency for minimum ionizing particles. The detection of K_L's and muons is consistent with expectations based on Monte Carlo simulations and the system should provide valuable information used for the measurement of CP violation parameters as well as many other physics processes.

7Acknowledgements

This work was supported by the U.S.-Japan Cooperative Research Program in High Energy Physics, the Japanese Ministry of Education, Science, Culture, and Sports, and the U.S. Department of Energy.
References


8 Figure Captions

Figure 1. The BELLE Detector.

Figure 2. Internal spacer and edge spacer cross-sections.

Figure 3. The endcap RPCs showing internal spacers. Barrel modules are similar, except rectangular in shape.

Figure 4. Cross-section of a superlayer module.

Figure 5. Cut-away view of an endcap superlayer module.

Figure 6. The gas mixing system.

Figure 7. The gas distribution system.

Figure 8. The gas exhaust and pressure control system.

Figure 9. Schematic of the RPC readout electronics.

Figure 10. The efficiency versus voltage.

Figure 11. The efficiency map of an endcap superlayer.
Figure 12. Spatial resolution of a superlayer.

Figure 13. Barrel superlayer efficiencies.

Figure 14. Endcap superlayer efficiencies.

Figure 15. Difference between the neutral cluster direction and the missing momentum direction.

Figure 16. Number of neutral clusters per event.

Figure 17. Muon detection efficiency versus momentum.

Figure 18. Fake rate versus momentum.