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Proposal for the BELLE muon system upgrade on the basis of scintillator technique

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PROPOSAL FOR THE BELLE MUON SYSTEM UPGRADE ON THE BASIS OF SCINTILLATOR TECHNIQUE /Preprint ITEP 28-02/

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The upgrade of the BELLE muon system is proposed on the basis of the scintillator techique. This would be reliable when operated at Super KEKB. Two options of scintillator geometry are considered: the strip and the pad ones, both with wave length shifting fiber readout. As possible photodetectors PMTs and new photodiodes working in Geiger mode are discussed. Estimates of phisical performance and cost for the proposed muon system are given.

ПРЕДЛОЖЕНИЕ ПО МОДЕРНИЗАЦИИ МЮОННОЙ СИСТЕМЫ ДЕТЕКТОРА BELLE НА ОСНОВЕ СЦИНТИЛЛЯЦИОННОЙ ТЕХНИКИ

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Предлагается усоверщенствование мюонной системы эксперимента BELLE на основе сцинтилляционной техники. Это стало бы надежным детектором при работе на ускорителе Super KEKB. Рассмотрены две опции геометрии сцинтилляторов: в виде полос и в виде квадратных пдастин, обе с использованием для считывания светосдвигающих волокон. В качестве возможных фотодетекторов осуждаются фотоумножители и новые фотодиоды, работающие в гейгеровской моде. Приведены оценки физических характкристик и стоимости для предлагаемого детектора.

Fig, - 12, ref. - 8 names.

I. INTRODUCTION

The BELLE K_L and muon detector (KLM) is based on resistive plate chambers (RPC) [1]. Already at the present background rate of about 0.1Hz/cm^2 in the end cap region RPC efficiency is about 95% only [2]. The background rate at Super KEKB is expected to be an order of magnitude higher. This will result in unacceptably low RPC efficiency (below 50%). It is believed that the background is dominated by neutrons. It might be possible to reduce the background somewhat by putting light material moderator after the lead shields at the detector sides facing the tunnel. However it is not easy to estimate the background rate. It will be known reliably only after commissioning of the Super KEKB and the upgrade of the BELLE detector. Therefore it looks more prudent to substitute RPC with a faster detector at least in the end cap region. KLM based on scintillator counters with wave length shifting (WLS) fibers can cope with the background rate at least two orders of magnitude higher than the present one. In this paper we discuss at a conceptual level properties of KLM based on scintillator technique and feasibility of its construction. The proposed system consists of two independent scintillator planes forming a superlayer in every gap in the magnet yoke. There are 15 superlayers in the barrel and 14 in the end cap. We consider two options: strip and tile scintillator shapes.

II. SCINTILLATOR STRIP OPTION

In this option the detector geometry is quite similar to the present one (see fig. 1 and fig. 2). The system consists of 35k scintillator strips with WLS readout arranged in two orthogonal planes in every gap in the magnet yoke. In the barrel the superlayers are split along z axis into two parts in order to reduce the maximum strip length. The scintillator strips have a cross section of 1.2cm×5cm and maximal length of 300cm. Scintillator light is caught by a WLS fiber and transported via a clear fiber to a region without magnetic field where Hamamatsu 64 channel PMs are placed. We consider also a possibility to put a photodetector in the magnetic field directly at the WLS fiber end. A so called Silicon Photo Multiplier (SiPM) is considered as

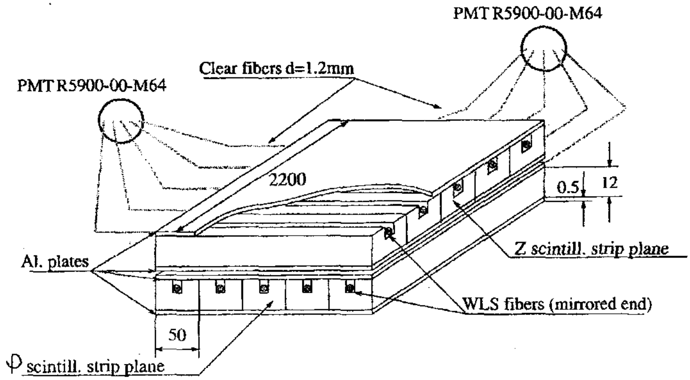

FIG. 1. *Schematic view of a KLM barrel superlayer for the scintillator strip option.*

a photodetector in this case. SiPM is a novel photodetector which is being developed in Russia [3]. It will be discussed in more details below. Individual strips are covered with a reflective cover. The strip has a groove in the center to accommodate a WLS fiber. The WLS fiber is glued to the scintillator. The WLS fiber is read out from one side. The far end of the WLS fiber is either mirrored or covered by a diffuse reflector. This improves the light yield from the far end of the strip by a factor of about 1.4.

The strips can be produced by injection moulding technique. Granulated polystyrene can be used as a base material with two dyes (1.5% of PTP and 0.01% POPOP). The strip length is limited by a mould to about 50cm. However longer strips can be made by gluing short strips together. Measurements show that the light yield drop near the joint is about 10% only. Another possibility is to use the extrusion technique. Very long strips can be produced with this technique.

The MINOS Collaboration has a lot of experience with the scintillator strips with the WLS fiber light collection. They use strips of 1cm×4.1cm cross section read out with Kuraray Y11 multiclading (MC) WLS of 1.2mm diameter. For minimum ionizing particles they observed on average 6 photoelectrons at 3 meters from the strip end (see fig. 3) using Hamamatsu R5900 M16 PM [4]. A similar light yield has been measured at ITEP for 1cm×2cm strips made in Russia during R&D studies for the OPERA experiment [5]. Five photoelectrons are required in order to have efficiency larger than 99%.

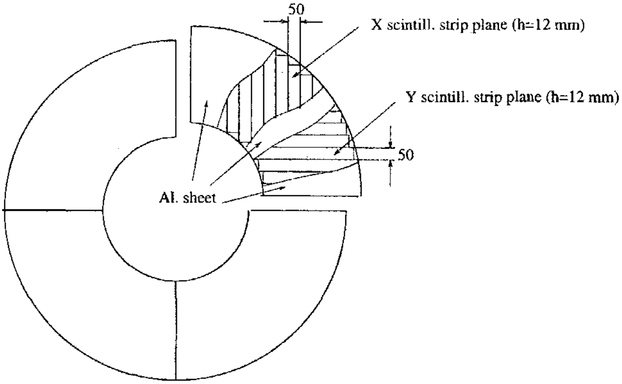

FIG. 2. *Schematic view of a KLM end cap superlayer for the scintillator strip option.*

Mirroring of the WLS fiber far end increases the light yield by about factor of 1.4 near the strip far end. This provides some safety margin which is very desirable since there is a large difference in the light yield between different strips. Some MINOS strips give only 4 photoelectrons at 3 meters from the strip end [4] (the yield should increase to about 5.5p.e. after fiber end mirroring). We have measured the light collection efficiency across a 1cm×4cm strip made in Russia. The efficiency is found to be uniform within ±5%. Detailed Monte-Carlo calculations predict only a factor of 0.9 smaller light collection efficiency for the 1.2cm×5cm strips which we propose to use. Hence they should provide enough light for MIP detection with high (>99%) efficiency. We can conclude that scintillator strips with WLS readout is a well established technique which is completely adequate for our application.

III. SCINTILLATOR TILE OPTION

Two scintillator planes in a superlayer can also be made out of scintillator tiles shifted by half a tile size in both directions (see fig. 4). The effective granularity in this case is one quarter of the tile size. Examples of possible WLS fiber and photodetector arrangements are shown in fig. 5. There are two advantages of the tile geometry. A tile from one plane overlaps with only four tiles from the second plane in a superlayer contrary to the strip layout in which a strip from one plane overlaps with all strips from the second

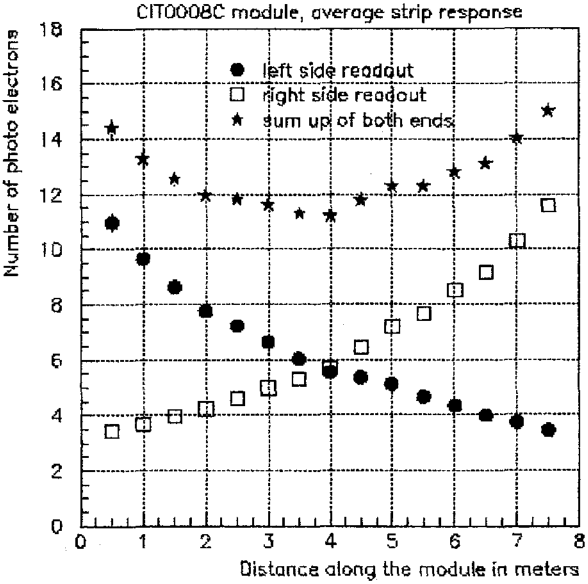

FIG. 3. *Signal pulse height for minimum ionizing particles as a function of a position along the MINOS scintillator strips.*

plane. This reduces drastically the number of random coincidences between two planes. The second advantage is a much better light collection efficiency which allows to set higher thresholds and hence to use intrinsically noisy photodetectors like SiPM.

Many scintillator and WLS fiber types have been tested at ITEP. Kuraray Y11 MC WLS fibers provide 70% more light than Bicron BCF-92 fibers. When the fibers are bent with 22mm radius the difference in light yield is 110%. Y11 fibers do not show any ageing after bending made at about 100°C at least for three months. We also have not observed any deterioration in the HERA-B electromagnetic calorimeter performance during 3 years of operation. This calorimeter contains 91k Kuraray MC Y11 1.2mm diameter fibers bended in the middle with a radius of 14mm [6]. It is however not easy to transform this information into a quantitative statement about the WLS fiber properties. More Kuraray WLS fiber ageing studies are being performed at ITEP now. Some samples of the Bicron BCF-91A WLS fiber demonstrated

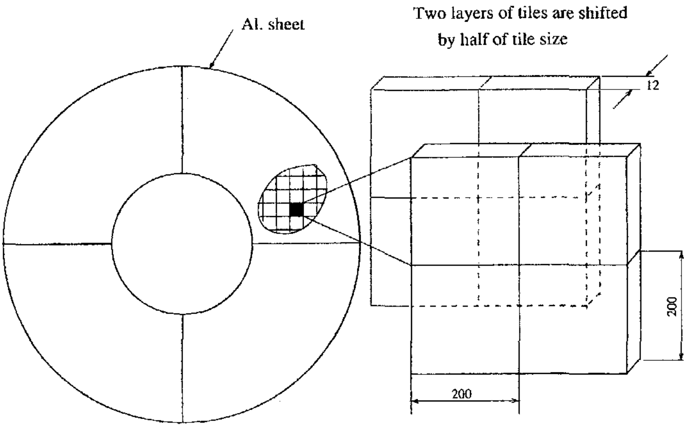

FIG. 4. *Schematic view of a KLM end cap superlayer for the scintillator tile option.*

fast (in days) ageing when bended with a radius of 22mm. Bicron BCF-92 samples were stable in time but provided less light than the Kuraray fiber. Thus the Kuraray MC Y11 WLS fiber fits better our application. Radiation load at BELLE is expected to be too small to cause any damage to scintillator or WLS fibers.

Table I shows the photoelectron yield for different scintillator types and tile sizes. The tile thickness was 5mm. The scintillation light from all tiles was collected with the same 60cm long Kuraray MC Y11 fiber. The fiber diameter was 1.0mm and its far end was covered by a diffuse reflector. Signals were detected with a Hamamatsu R329-02 PM which has a quantum efficiency of about 10% near the maximum of the WLS fiber spectrum. The fiber was placed without gluing into circular 2.5 mm deep groove. The groove diameter was about 0.9 of the cell size. The photoelectron yield was corrected

TABLE I. *Light yield (p.e.) for 5mm thick scintillator tiles with circular grooves.*

Tile size	SCSN-81	Protvino	Vladimir	Vladimir, 2 turns	BC-408
5cm × 5cm	7.3	10.0	9.6	13.6	16.3
7cm × 7cm	9.4	10.6	10.9	15.8	20.4
9cm × 9cm	7.3	9.5	9.5	13.5	16.6
16cm × 16cm	6.2	6.4	6.0	9.3	

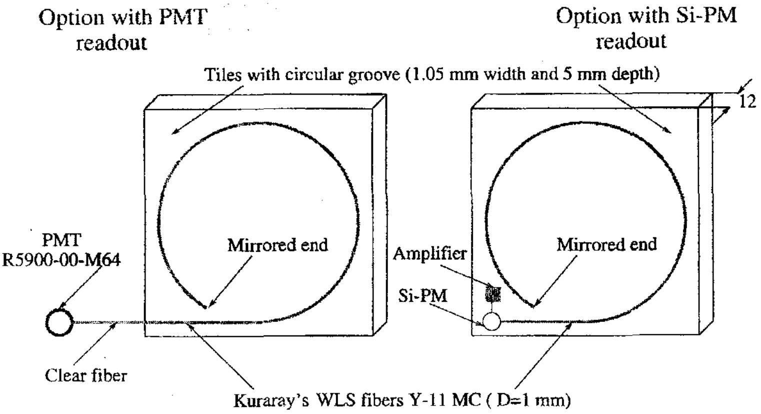

FIG. 5. *Individual scintillator tile setup.*

for the light losses in the fiber outside the tile since in the final design the WLS fiber ends at the tile end (see fig. 5). Bicron BC-408 scintillator gives more light than SCSN-81 and Russian scintillators made in Vladimir and Protvino. However it is an order of magnitude more expensive and therefore will not be discussed further. The Russian scintillators provide enough light for efficient detection of minimum ionizing particles. The photoelectron yield in the proposed design will be at least factor of 2.5 higher than in table I since the scintillator thickness will be 2.4 times larger and the fibers will be glued to the scintillator.

Different WLS fiber shapes have been investigated: straight fiber at a tile side and in the center, diagonal and quarter of a circle fibers. The last two provide acceptable light yield and uniformity. However, the circular fiber provides the highest light yield and the best uniformity. Fig. 6 shows the light yield uniformity in a 16cm×16cm tile with a circular WLS fiber. It is flat within ±5% with exception of a region where the WLS fiber exits the tile. If necessary the increase in this region can be reduced by shortening the fiber length.

It is possible to conclude that the tile option is also feasible. It provides larger photoelectron yield and better random background suppression than the strip option but requires twice larger number of channels.

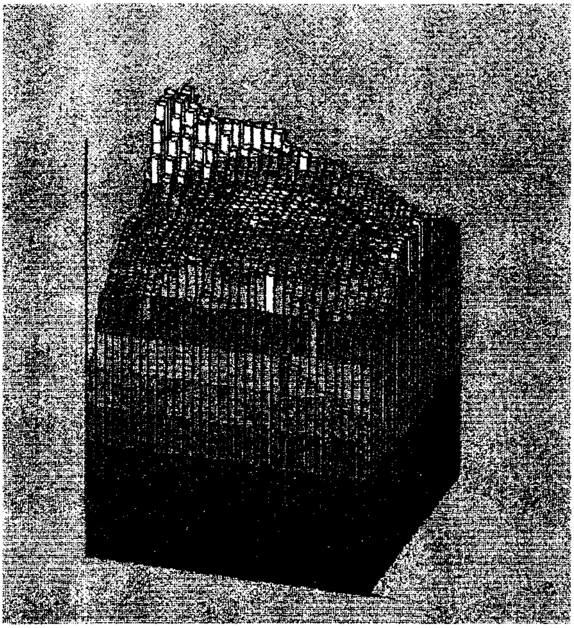

FIG. 6. *Light yield from* $16 \times 16 \times 0.5cm^3$ *tile with circular WLS.*

IV. PHOTODETECTORS

Several photodetectors can be used for the WLS fiber readout. In this paper we discuss only two examples: multichannel PM and SiPM. Multichannel PM is a well proven technique which is completely adequate for our application. Hamamatsu R5900 64 channel PM is the most cost effective solution [7]. Each individual channel of this PM can work at a rate of 3×10^7Hz of single photoelectron pulses with a gain of 5×10^5. This is three orders of magnitude larger than the expected background rate of about 10^4Hz per strip (see below). It is expected that the background is dominated by few photoelectron signals. The life time of PM at maximum rates is above 200 years. R5900 M64 quantum efficiency is about 13% at the maximum of the WLS fiber spectrum. It is practically identical to the quantum efficiency of R5900 M16 PMs which are used by the MINOS Collaboration and provide sufficient number of photoelectrons.

There are however several drawbacks in this solution. First of all PM can not work in a strong magnetic field of BELLE. Therefore the light should be transported by clear fibers to a field free region. This complicates considerably the system design and assembly. There is also considerable cross talk between neighboring PM channels. The cross talk to all neighbor channels is about 8% even if the fiber is positioned at a center of a 2x2mm^2 cell. About half of the cross talk signals produce fake hits in strips geometrically separated from a strip with a genuine signal. This leads to ghost coincidences between strips in two planes of a superlayer. Another half of cross talk signals produce fake hits in strips neighboring to a strip with a genuine signal. This leads to some deterioration of spatial resolution. Finally there is a large (up to a factor of 3) difference in gain between individual channels. This difference can be compensated by preamplifiers with adjustable gain. In spite of these drawbacks R5900 M64 photomultipliers are adequate and completely ready for our application.

An alternative solution for the photodetector could be a Silicon PM - a novel detector which is being developed in Russia [3]. SiPM is a matrix of 576 tiny ($42 \times 42 \mu m^2$) silicon photodiodes working in a Geiger mode (see fig. 7 [3]). Every photoelectron produces a standard signal with an amplitude which depends on the diode capacity and bias voltage. A typical amplification is about 10^6. Signals with different number of photoelectrons are well separated (see fig. 8 [3]). The output signal is proportional to the number of photoelectrons as long as this number is small in comparison with the number of pixels in SiPM. Spectral sensitivity of SiPM matches well a typical WLS fiber spectrum. Geometrical efficiency of SiPM is about 25% now and can be increased to about 40% in future. The product of quantum and geometrical efficiency is 15-19% in the region near the WLS fiber spectrum maximum (see fig. 9 [3]). This is slightly higher than the quantum efficiency of R5900 M64 PM and will be further improved. SiPM can work at much higher rates than the required rate of 10^4Hz. However its lifetime at such rates has still to be measured.

There are several advantages of SiPM with respect to multichannel PM. SiPM is tiny and can work in a strong magnetic field. Therefore it can be placed at the WLS fiber end avoiding the light transportation with clear fibers. Several such tile counters with SiPM attached directly to the WLS fiber have been built at MEPhI and ITEP. Fig. 10 shows a distribution of

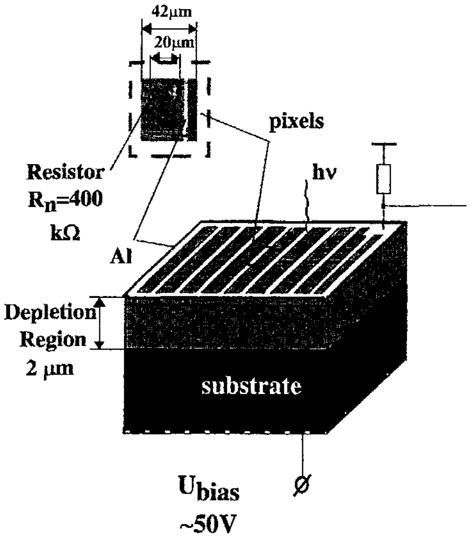

FIG. 7. *Schematic view of Silicon PM.*

minimum ionizing particle signals observed with such counters (signals from three 5mm thick scintillator tiles read out with SiPM were added together). SiPM is expected to be twice cheaper than one channel of R5900 M64 PM. There is no cross talk problem and no big variation of response from channel to channel.

However there are also disadvantages. SiPM has quite high noise rate of about 2MHz at room temperature (see fig. 10). In order to make it comparable with the expected physics background rate one has to put threshold at a few photoelectrons which decreases the efficiency in the strip option. In the tile option the photoelectron yield is larger such that the higher threshold does not practically influence the efficiency. By relaxing the requirement on the noise rate to about 0.1MHz one can lower the threshold and obtain the average strip efficiency of about 98%.

We can conclude that SiPM is a very attractive choice for the photodetector. Unfortunately this device is still in a R&D stage and it is not clear whether it will be ready for practical applications in time for the BELLE

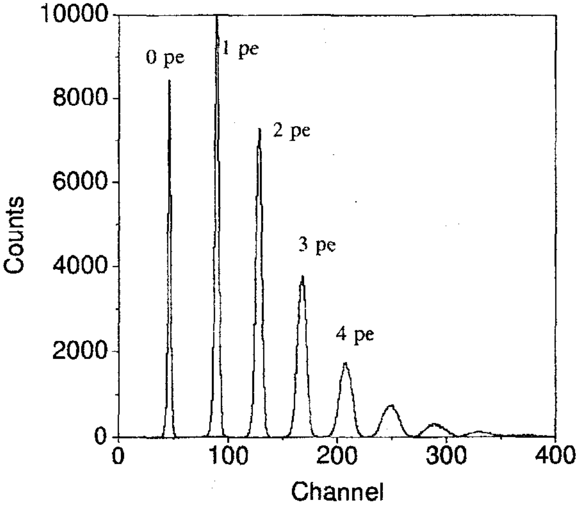

FIG. 8. *Single photoelectron (single pixel) spectra of SiPM.*

KLM upgrade.

V. PERFORMANCE

Scintillator KLM can work efficiently at background rates 100 times larger than the present one.

It has much lower sensitivity to background than RPC. Background neutron or γ is absorbed in one scintillator strip or tile, so there are no two dimensional hits from single background particles. This is in contrast to RPC, where even single neutron or γ produces a two dimensional hit.

Scintillator counters are much less sensitive to photon background than RPC because most of photons have by far smaller energies than the energy deposited in scintillator by minimum ionizing particles. It is however believed that the major background in BELLE KLM is due to neutrons. Scintillator counters are typically more sensitive to neutrons than RPC although the ratio of sensitivities depends strongly on the neutron spectrum. Gaseous detectors without hydrogen in the active volume are mainly sensitive to photons produced by neutrons [8]. This results in a cathode strip chamber sensitivity of about 0.5% for neutron spectrum typical for hadron colliders. Scintillator

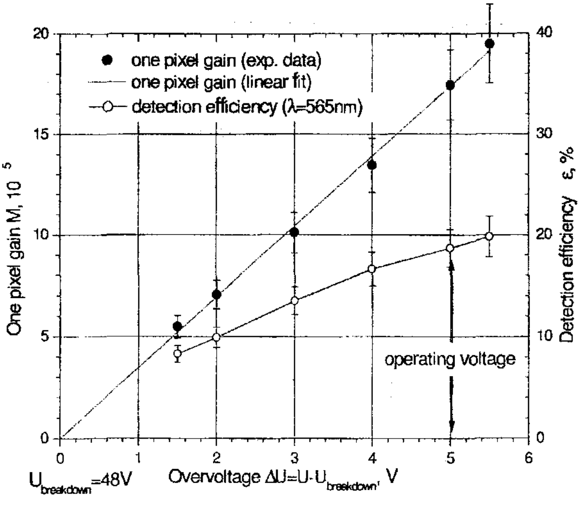

FIG. 9. *Efficiency of SiPM vs overvoltage.*

efficiency to such neutrons is in a few percent range. Therefore we assume conservatively that scintillator counters will be ten times more sensitive to background neutrons than RPC. The rates of KLM clusters originating from random coincidences of background hits in independent planes of a superlayer are presented in table II. The numbers are given for the background hit

TABLE II. *The numbers of KLM clusters per event originating from random coincidence of background hits in independent planes of a superlayer. The assumed flux of background particles is* $10^5 Hz/m^2$ *and time resolution is 30nsec. Correlated background is not taken into account.*

	#layers ≥ 1	#layers ≥ 2
scintillator strip option	0.03	10^{-7}
scintillator tile option	0.001	2×10^{-10}

rate of $10^5 Hz/m^2$ (10 times higher neutron flux than the present one and 10 times higher sensitivity to neutrons of scintillator than of RPC) and for time resolution of 30nsec. The KLM cluster is defined in a usual way except that only adjacent layers are used. The random background rate is negligible, therefore we expect that the background will be dominated by consecutive

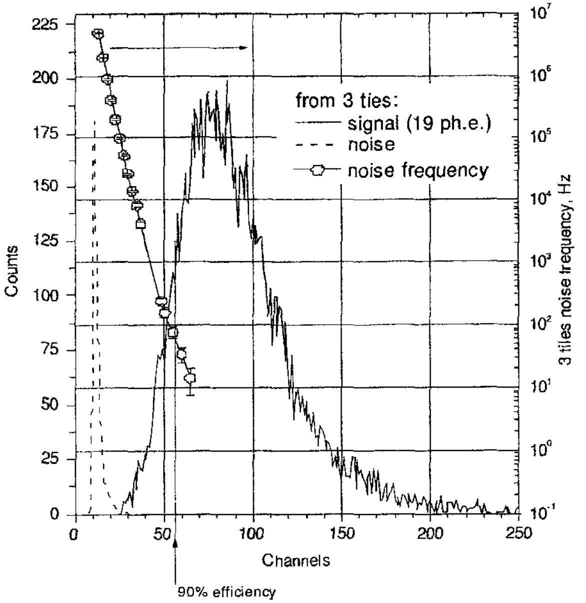

FIG. 10. *Minimum ionizing particle signals detected with three 5mm thick scintillator tiles read out with SiPMs.*

scattering of the same neutron in adjacent counters. The corresponding rate has still to be estimated.

Even at present background level a fraction of K_L originating from background in the RPC KLM is considerable. Table III presents the rates of neutral KLM clusters obtained from a Monte-Carlo simulation of three event types: $B\bar{B}$, $B\bar{B}$ with background added and background only. The presence of background increases the rate of K_L candidates by 30% (last column in table III), the main contribution coming from random coincidences of ECL clusters and KLM background clusters. The distribution of fake K_L candidates peaks in the highest occupancy region at large $\cos\theta$ as seen in Fig. 11.

In the present reconstruction algorithm a neutral KLM cluster is considered as a K_L candidate if its number of layers is larger or equal to two or if there is a matching ECL cluster. Low background rate in the scintillator KLM suggests that one can consider also 1-layer clusters as K_L candi-

TABLE III. *The number of neutral KLM clusters per event obtained from Monte-Carlo simulation for $B\bar{B}$ events, $B\bar{B}$ events with background added and background events only. Background from experiment 13 is used.*

	matching ECL cluster	no ECL, #layers = 1	no ECL, #layers $\geq$ 2	matching ECL or #layers $\geq$ 2
$B\bar{B}$	0.18	0.73	0.19	0.37
$B\bar{B}$ + bg	0.34	2.4	0.23	0.56
only bg	0.003	1.8	0.03	0.03

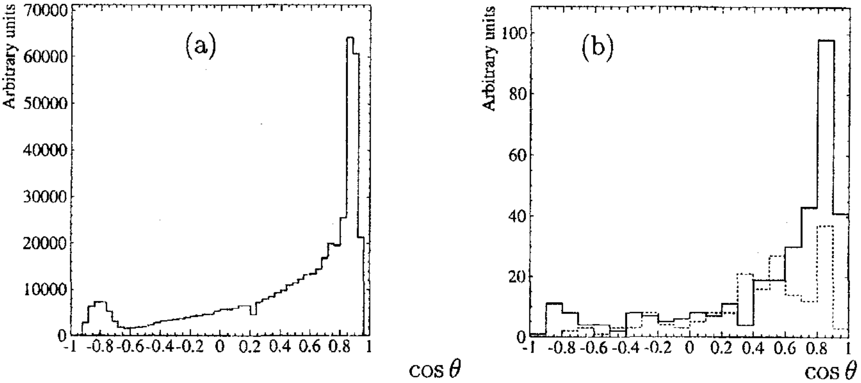

FIG. 11. *Polar angle distribution of K_L candidates (a) for data, (b) for Monte-Carlo simulated events (solid line - $B\bar{B}$ events with added background, dashed line - only $B\bar{B}$ events). Background from experiment 13 is used. Monte-Carlo events do not contain continuum contribution.*

dates. The resulting increase in efficiency is shown in Fig. 12 (a), it is more pronounced at low momenta. The spectra of K_L from $B \to J/\psi K_L$ and $B \to J/\psi K_L \pi^0$ decays are shown in Fig. 12 (b). The use of 1-layer clusters will add 0.7 fake K_L candidate/event due to large angle tracks from hadron showers.

VI. COST ESTIMATE

A very preliminary cost estimate has been made for the strip option with multichannel PM read out (see table IV) and for the tile option with the SiPM read out (see table V). The cost estimates do not include several

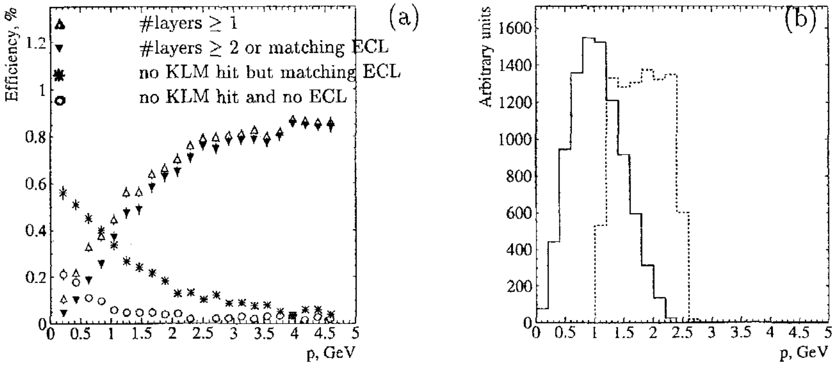

FIG. 12. *(a) K_L efficiency vs. momentum for present reconstruction algorithm (#layers ≥ 2 or matching ECL cluster) and for considered use of 1-layer clusters in addition. Inefficiency due to absence of KLM hits (with and without matching ECL cluster) is also plotted. (b) spectra of K_L from $B \to J/\psi K_L \pi^0$ decays (solid line) and $B \to J/\psi K_L$ decays (dashed line).*

minor items. However this should not change the cost considerably. Data acquisition and trigger systems are not discussed in this paper and their costs are not given in the tables.

VII. CONCLUSIONS

KLM based on scintillator counters with WLS fiber light collection can work efficiently at the background rates 100 times larger than the present one. This is a well established experimental technique in case of multichannel

TABLE IV. *Cost estimate for the strip option.*

Strips	#35000, 46000kg	322k$
WLS fibers	70km	105k$
Clear fibers	105km	105k$
Clear fiber connectors	#35k	35k$
PMT R5900-M64	#550	770k$
Power supplies & cables		30k$
Preamplifiers	35k	50k$
Total		1417k$

TABLE V. *Cost estimate for the tile option.*

Tiles	#90000, 43200kg	303k$
WLS fibers	108km	162k$
SiPM	#90000	900k$
Power supplies & cables		20k$
Total		1385k$

PM readout. It is even more attractive and elegant with the SiPM readout. However in this case a lot of R&D is still required. A lot of optimization and tests should be done for both strip and tile options.

VIII. ACKNOWLEDGMENTS

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