

Status of the Super KEK B factory

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Abstract. We are preparing a major upgrade of the KEKB electron-positron collider, the Super KEK B factory (*SuperKEKB*) – a project that could detect new phenomena arising from physics beyond the Standard Model by using a large amount of data, corresponding to the integrated luminosity of 50 ab^{-1} . This data set will allow studies of rare processes in B meson decays, D meson decays and τ lepton decays with an unprecedented sensitivity. To achieve the goal of this ambitious project, the design luminosity of the SuperKEKB is $8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ – 50 times larger than that of the present KEKB collider. The current Belle detector will also be upgraded to take a full advantage of the high collider luminosity. The new detector, SuperBelle, is designed in such a way that it should perform at least as well as the present Belle spectrometer, despite the substantial increase in beam-induced backgrounds.

1. Introduction

Successful studies of CP violation in B meson decays, which were performed by measurements of the time-dependent decay rate asymmetries, have confirmed the experimental potential of two e^+e^- high luminosity colliders, so-called B factories: KEKB in Japan and PEP-II in the USA with their adjacent detectors, Belle and BaBar, respectively. These results have – together with measurements of sides and angles ϕ_1 , ϕ_2 and ϕ_3 of the Unitarity Triangle (UT) – confirmed that the Kobayashi-Maskawa mechanism explains at least the dominant source of all CP violating phenomena in the Standard Model (SM) of particle physics. Such an achievement of B factories was possible only due to two orders of magnitude higher luminosity than existing experiments had at that time, and with a concept of asymmetric electron and positron beam energies, which provided a boosted centre-of-mass frame in e^+e^- collisions.

Large amount of data at B factories and excellent detector performance – Belle alone has so far accumulated a data set of about 900 ab^{-1} , containing 850 million $B\bar{B}$ pairs – have enabled also many other tests of the Standard Model. Among the most important are: the observation of direct CP violation in B decays, measurements of rare B decay modes (e.g., $B \rightarrow \tau\nu$, $B \rightarrow D\tau\nu$) and observation of neutral D meson mixing. In addition, large amount of data enabled discoveries of new hadronic states and studies of their properties, as well as extensive measurements and searches for various τ lepton decays.

However, albeit the SM has successfully passed various experimental tests, it is still considered that a more fundamental physics beyond the SM (BSM) exists. The idea that the SM is just a low-energy approximation of a more general BSM theory is supported by the existence of many

¹ The name for the new collaboration/detector is still to be selected; *SuperBelle* is used in this paper.

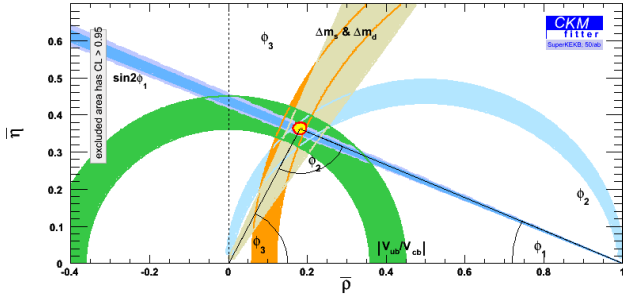


Figure 1. Expected SuperKEKB sensitivities for the UT measurements with 50 ab^{-1} data. (Current world average values are used for the central values in the plot.)

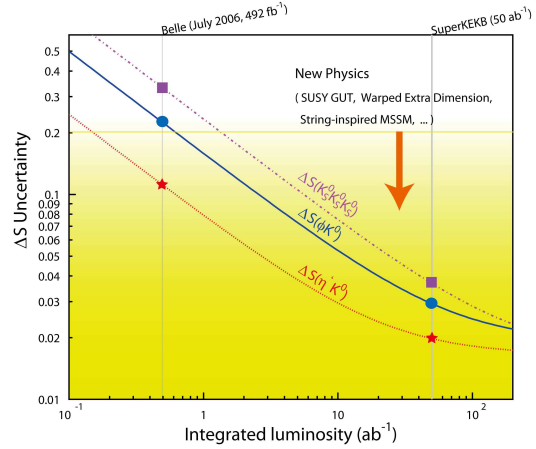


Figure 2. Expected sensitivities of the CP -violation measurements in $B \rightarrow \phi K_S^0$, $B \rightarrow \eta' K_S^0$ and $B \rightarrow K_S^0 K_S^0 K_S^0$ decays as a function of the integrated luminosity.

questions, which remain unanswered even after several decades of comprehensive theoretical and experimental particle physics research. One of these questions is whether there exist new CP -violating phases responsible for the baryon-number asymmetry in the universe, as this asymmetry cannot be explained by CP violation in the SM. A serious theoretical argument for the SM extension comes also from the solution to the hierarchy problem, which suggests that in order to be able to cancel the quadratically divergent radiative Higgs mass corrections, the BSM physics at the TeV energy scale is required. On the other hand, the so-called flavour problem indicates that the new physics energy scale should be larger than 1000 TeV, if strong constraints on the flavour changing neutral current (FCNC) amplitudes from existing B factory measurements are taken into account. Any BSM physics at the TeV scale should therefore have a mechanism to suppress FCNC processes, which would give it a distinctive flavour structure at low energy. Precise flavour physics measurements would thus enable observations of possible deviations from the SM, as well as help distinguishing between different BSM models. Studies of a large number of B meson decays in the clean e^+e^- environment seem to provide a perfect tool for this purpose – a tool not available neither at the Large Hadron Collider (LHC) nor at the future linear collider. To observe the effects of the BSM physics, which should in most cases appear through the loop diagrams, it is necessary to construct a new experimental facility – the SuperKEKB factory – with the luminosity that is again about two orders of magnitude larger than at present B factories. Within a decade, this should enable to collect the data set, corresponding to the integrated luminosity of 50 ab^{-1} .

The key measurements at the new experiment will still be the measurements of the UT, but they will be an order of magnitude more precise than the current ones. Expected sensitivities of the UT measurements with the full data set (see Fig. 1) indicate that an $\mathcal{O}(10\%)$ deviation from the SM in any of the measured parameters should be observed. One of the most promising measurements to search for the BSM signature in the UT parameters is the extraction of the angle ϕ_1 for loop dominated $b \rightarrow s$ decays. In the SM, these flavour-changing transitions can only proceed through penguin loop diagrams. The dominant $b \rightarrow s\bar{q}q$ penguin diagrams include the same weak phase as $b \rightarrow c\bar{c}s$ decays, so in the first order the time-dependent CP -violation coefficients \mathcal{S} are predicted to be the same, i.e. $\mathcal{S} = \sin 2\phi_1$. An additional BSM amplitude could modify the $b \rightarrow s\bar{q}q$ phase via the penguin loop diagram, while the $b \rightarrow c\bar{c}s$ phase would

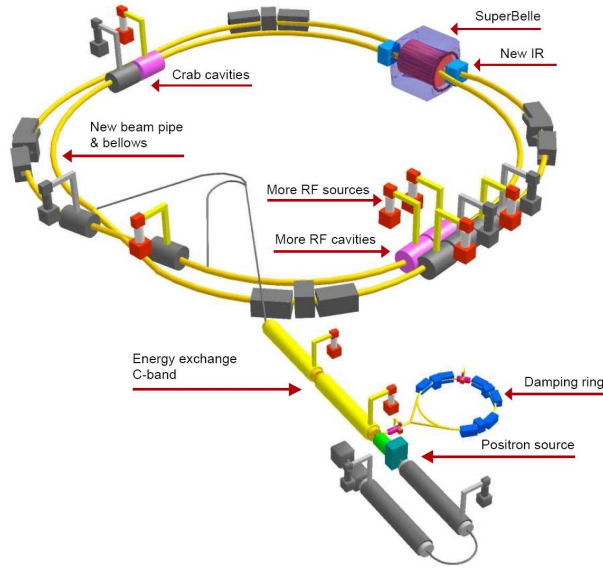


Figure 3. Schematic layout of the accelerator upgrade for the SuperKEKB.

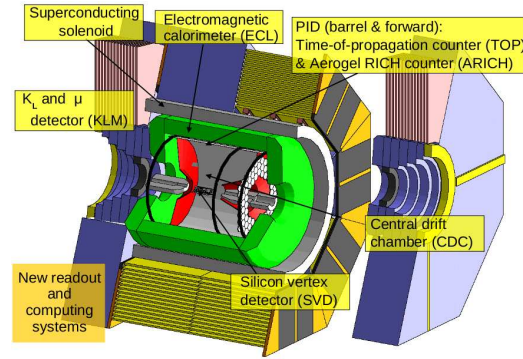


Figure 4. Conceptual design of the SuperBelle spectrometer in three-dimensional view.

be unaffected. The difference between $\sin 2\phi_1$ for $b \rightarrow c\bar{c}s$ and \mathcal{S} for $b \rightarrow s\bar{q}q$ decays would then indicate the existence of the BSM physics. However, differences from $\sin 2\phi_1$ are already expected within the SM, since various processes with more than one weak phase contribute significantly to $b \rightarrow s\bar{q}q$ amplitudes and thus complicate the interpretation. The three decays whose \mathcal{S} coefficients are the least affected by the SM modifications (0.02 change), are considered to be the “golden” modes for the BSM searches: $B \rightarrow \phi K_S^0$, $B \rightarrow \eta' K_S^0$ and $B \rightarrow K_S^0 K_S^0 K_S^0$. As shown in Fig. 2 these CP -violation measurements are still expected to be limited by statistics before the 50 ab^{-1} of data is collected at the SuperKEKB.

Many other measurements, sensitive to the BSM physics, will also be performed at the SuperKEKB, such as: searches for the right-handed weak currents through the non-zero \mathcal{S} value in a time-dependent CP violation measurement for the $B \rightarrow K_S^0 \pi^0 \gamma$ decay; searches for a charged Higgs boson in $B \rightarrow \tau \nu$, $B \rightarrow D^{(*)} \tau \nu$ and $B \rightarrow \mu \nu$ decays; inclusive measurements as $B \rightarrow X_s \gamma$, $B \rightarrow X_d \gamma$ and $B \rightarrow X_s \ell^+ \ell^-$, which are sensitive to various BSM scenarios. SuperKEKB will also be a D and τ factory: a measurement of CP violation in $D^0 - \bar{D}^0$ mixing, or an observation of lepton-flavour-violating τ decays would be clear evidence for the BSM physics. These and other possible measurements at the SuperKEKB have been studied in detail and these reports can be found in Ref. [1, 2, 3]. One important issue for the SuperKEKB factory is that its physics motivation is independent of the LHC: If the LHC finds BSM physics, precision measurements in flavour physics are compulsory; if no deviations from the SM are found, a high statistics sample of B mesons, D mesons and τ lepton decays would still allow a unique way to search for the TeV scale physics.

This paper presents one possible scenario for significant enlargement of the current data sample by upgrading the existing KEKB collider [4] and the Belle spectrometer [5] to SuperKEKB and SuperBelle, both shown schematically in Fig. 3 and Fig. 4. Since the Letter of Intent [6], many R&D studies have been performed on the fundamental performance of the sensors, material structure and geometry of the collider and the detector [7]. In what follows, the design of both will be summarised.

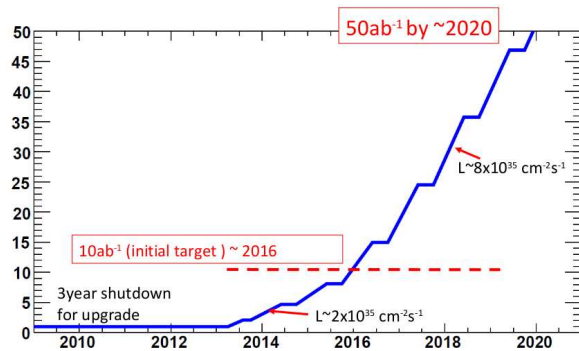


Figure 5. Plan for the SuperKEKB integrated luminosity increase.

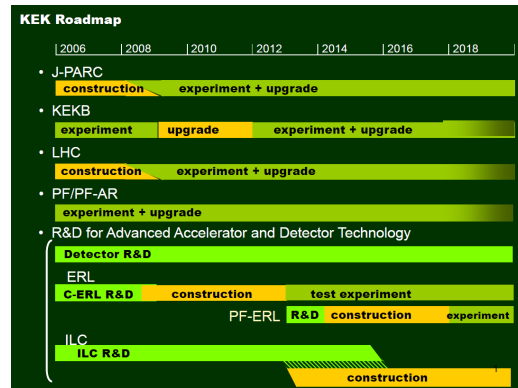


Figure 6. KEK's experimental roadmap.

2. The SuperKEKB collider

The current KEKB collider [4] will be replaced by the similar colliding machine, called the SuperKEKB, with the peak luminosity that is about 50 times larger than that of the present KEKB factory. This goal will be reached by increasing the number of electron and positron bunches and the beam currents, and by improving the beam optics in the interaction region. In order to minimise the cost of the accelerator upgrade, the new machine will be placed in the existing tunnel and most of the KEKB components will be re-used, especially the ring magnets and the klystrons used to supply RF power to the cavities. The schematic layout of the accelerator upgrade is depicted in Fig. 3

Two major phases are foreseen for the gradual increase in the luminosity of the accelerator (see Fig. 5). For the first phase, which includes the three-year shutdown period and is supposed to finish within the next five years, the luminosity target is set at $2 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. This target should be achieved by several improvements: the interaction region will be redesigned and crab cavities will be installed on both sides of the interaction region; beam currents will be increased; new beam pipes with ante-chambers will be installed. An increase of the luminosity to the design value of $8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ is planned for the second phase of the upgrade: During the next five-year term, between 2014 and 2019, a further increase in the beam currents and an installation of a dumping ring for electrons and positrons is foreseen.

The KEKB upgrade plan is already included in the KEK's five-year road map from 2009 to 2014 as shown in Fig. 6. According to plans, 8 years of SuperKEKB operation will enable SuperBelle collaboration to collect a large sample of $B\bar{B}$, $D\bar{D}$, and $\tau^+\tau^-$ pairs corresponding to a total integrated luminosity of 50 ab^{-1} , necessary to achieve the ambitious physics goals.

3. The SuperBelle detector

An increased luminosity results in higher event rates: at a luminosity of about $1 \cdot 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ the $B\bar{B}$ production rate alone is about 1 kHz, and the physics trigger rate will be more than 10 kHz. In order to cope with these rates and keep high physics efficiencies, the existing trigger and data-acquisition systems need to be redesigned and substantially improved. The used read-out electronics should also introduce as little dead time as possible. On the other hand, the high-luminosity accelerator upgrade results also in the increased level of the beam-induced background, such as: beam scattering on the residual gas; Touschek (intra-bunch) scattering; direct synchrotron radiation (SR) and the back-scattered SR component; and radiative Bhabha scattering. The total estimated background will be about 20 times higher than in the current Belle detector [5], which will thus also have to be substantially modified in order to be able to

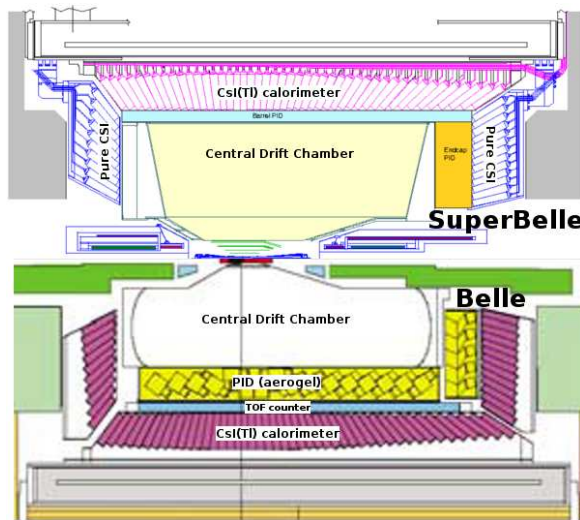


Figure 7. Comparison between the SuperBelle (top) and Belle (bottom) inner parts.

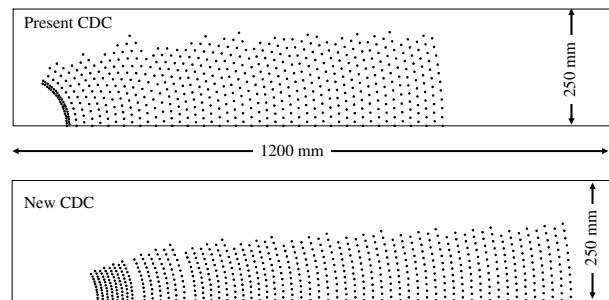


Figure 8. Configuration of CDC sense wires in the present (top) and the new CDC (bottom).

cope with much higher occupancies and more radiation damage. The final requirement for the upgraded detector, SuperBelle, is that its minimal performance in the harsh beam-background environment should be at least as good as the performance of the current Belle spectrometer.

The new detector has to be hermetic in order to enable successful photon/ π^0 detection and neutrino reconstruction from the missing energy and momentum. Also, the upgraded detector should provide low momentum μ identification to increase the $b \rightarrow s\mu^+\mu^-$ reconstruction efficiency. The design of the SuperBelle detector is – similarly as Belle – based on these requirements: the SuperBelle is foreseen to be a general purpose spectrometer inside a superconducting solenoid providing a uniform magnetic field with a density of 1.5 T. The spectrometer will consist of the following components: a vertex detector used for the determination of the decay-vertex positions of long-lived beauty, charmed and strange hadrons; a central tracker measuring the momentum and the specific ionisation (dE/dx) of charged tracks; barrel and end-cap calorimeters that measure the energy and determine the position of photons, electrons and neutral pions; barrel and end-cap particle identification devices distinguishing kaons from pions and muons; and a K_L/μ detector, which is instrumented in the magnetic-flux return yoke. Finally, a fast and reliable trigger and data acquisition systems are designed in order to efficiently process and record events measured by the detector. The computing and data storage are planned to be distributed globally at various participating laboratories. Main features of the subdetector components, shown in the three-dimensional view of the SuperBelle spectrometer in Fig. 4, are briefly described in the following subsections.

3.1. Vertex detector

The vertex detector is a crucial subdetector component, necessary for a precise determination of the decay-vertex position of produced long-living particles. The vertex information also helps reducing the track-reconstruction errors.

The planned silicon vertex detector (SVD) will be constructed around a 1.5 cm beam pipe and will consist of six layers of double-sided silicon-strip sensors. The modified vertex detector will have larger radius than the present Belle vertex detector and will thus also replace the inner part of the current Belle drift chamber. This should enable a more robust particle tracking,

improve the tracking efficiency for low momentum particles and result in higher $K_S \rightarrow \pi^+\pi^-$ reconstruction efficiency. In order to reduce the vertex detector occupancy due to the beam background, VA1TA read-out chips will be replaced with APV25 chips [6], and a pipeline read-out scheme will be implemented for the front-end electronics.

In order to improve the vertex resolution, an installation of a new beam pipe with a smaller radius of 1 cm and a new innermost vertex detector layer is foreseen after a few years of operation. The pixel sensors, which can operate at the high beam-background level, are planned for this upgraded first vertex layer.

3.2. Central Drift Chamber

The present Central Drift Chamber (CDC) has been working well since the beginning of the Belle experiment. The CDC enables charged-track reconstruction with good momentum resolution due to the small amount of material, which reduces multiple scattering. It also enables charged-particle identification by measurements of the characteristic energy loss (dE/dx). Fast response of the CDC is also used as a powerful trigger signal with a latency of only a few μs .

All required features of the CDC can be achieved by a small-cell wire chamber filled with a helium-based gas. The overall new detector shape is similar to the present CDC, but due to severe beam background the inner radius of the chamber will be increased and the volume replaced by two layers of the vertex detector (Fig. 7). The outer radius of the new drift chamber will be larger because of the thinner barrel part of the particle identification device. The cell size of the inner layers in the new CDC will be smaller in order to reduce the occupancy and shorten the drift time (Fig. 8). Consequently, more stereo layers should also improve three-dimensional track reconstruction.

3.3. Particle identification system

To extend the SuperBelle physics reach, the K/π separation capability up to momenta of 4 GeV/c is required despite the higher-background environment. This is a very important requirement for the upgraded particle identification (PID) system. In addition, the new detectors should also be made with a reduced amount of more uniform material, since the PID system is located in front of the calorimeter. The existing time-of-flight system and aerogel threshold Cherenkov counters will therefore be replaced by detectors for Cherenkov ring image reconstruction: a time-of-propagation counter (TOP) in the barrel part and an aerogel ring imaging Cherenkov counter (ARICH) in the forward end-cap part of the SuperBelle detector.

In the TOP counter the time of propagation of the Cherenkov photons internally reflected inside a quartz radiator is measured (Fig. 9). The Cherenkov image is then reconstructed from the two-dimensional information provided by one of the coordinates (x) and a precise timing, which are both determined by position sensitive micro-channel plate (MCP) photomultipliers at the end surfaces of the quartz bar. The TOP detector will be composed of the array of 18 modules, surrounding the outer wall of the CDC. The modules will consist of 2 cm thick quartz radiator bars with a width of 40 cm and with the attached photodetector array. In each of the modules the quartz radiator bar is subdivided into two pieces, in order to reduce the possible resolution degradation due to chromatic dispersion.

The ARICH counter will be located in the region of the existing forward end-cap aerogel counter. Due to the limited space, a proximity focusing RICH counter with aerogel Cherenkov radiator and light expansion distance of 20 cm will be used. The particle separation is improved by using three layers of silica aerogels as radiators. Each layer will be 10 mm thick, with different refractive indices varying from 1.045 to 1.055, so that Cherenkov photons will produce overlapping images on the photon detector surface, as shown in Fig. 9. The photon detector, which has to detect single photons and be able to operate in the 1.5 T magnetic field, is still

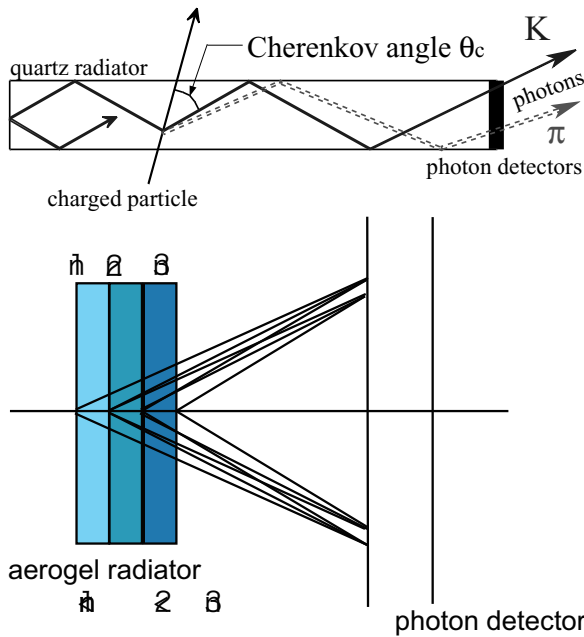


Figure 9. Schematic views of the PID detectors: the TOP counter with internal reflecting Cherenkov photons (top); the ARICH counter with multiple aerogel radiators (bottom).

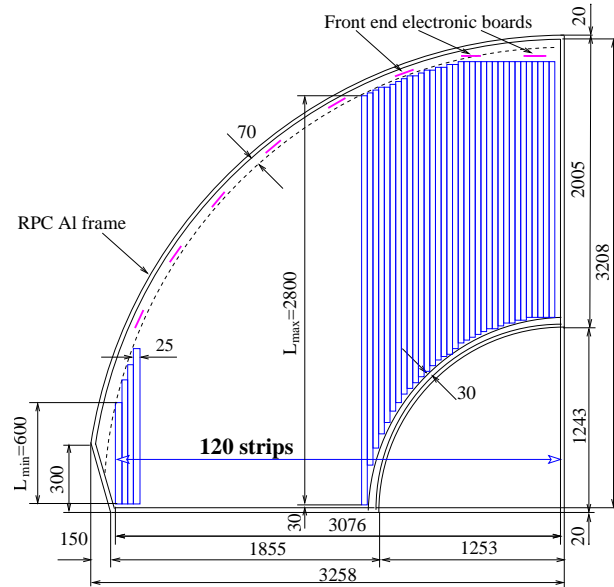


Figure 10. An illustration of one quadrant of the KLM scintillator-strip superlayer.

to be chosen among three candidates: a hybrid avalanche photon detector (HAPD), micro-channel plate photomultiplier (MCP-PMT) or Geiger mode avalanche photo-diode (GAPD). If MCP-PMT is selected, its timing resolution of ~ 50 ps for single photons would allow an additional time-of-flight measurement by using the Cherenkov photons from the entrance window of the MCP-PMT. With this method, charged kaons with momenta even below the Cherenkov threshold in aerogel (≈ 1.5 GeV/ c) could be identified.

3.4. Electromagnetic Calorimeter

Due to higher beam currents the background in the electromagnetic calorimeter (ECL) is expected to be an order of magnitude larger than at the present Belle ECL, thus resulting in many fake clusters and a pile-up noise.

The basic idea of the ECL upgrade is to replace the present read-out electronics. The new front-end electronics with $0.5 \mu s$ (instead of $1 \mu s$) shaping time will be used. In addition, waveform shaping with a ~ 2 MHz sampling frequency will be implemented. Both the energy and the timing are extracted from the sampled waveform, thus allowing a separation between physics signal and beam backgrounds.

The background-rejection capability of the waveform analysis is limited by the slow ($\sim 1 \mu s$) scintillation light of the existing thallium-doped CsI crystals. While these CsI(Tl) crystals can still be used for the barrel part of the new ECL, the end-cap part of the new calorimeter will be replaced with pure CsI crystals with a fast time constant of 30 ns, but smaller light output. The scintillation light will thus have to be read by special high-mesh photomultipliers with a small number of multiplication stages that can achieve a gain of more than 20 even in 1.5 T magnetic field. Altogether, pure CsI crystals and a proper waveform analysis should help reduce the background by more than a factor of 100.

3.5. K_L and μ detector

The performance of the currently installed resistive plate counters (RPCs) is expected to be degraded in the SuperKEKB environment due to high rates of neutrons, which represent the dominant background and cause long dead time in the K_L and μ detector (KLM).

In the barrel part of the new KLM detector the shorter dead times and thus the improvement in efficiency can be achieved by using the modified gas mixture. Another method to suppress the neutron background, is the replacement of the innermost RPC layer with a 4 cm thick passive polyethylene absorber. Both of these modifications are expected to help restore the efficiency of the barrel KLM detector to only a few % below the existing efficiency despite much higher neutron background.

In the end-cap parts of the KLM, where the efficiency drop due to the background is larger, the RPCs will be replaced with new and faster detection devices: scintillator counters with wavelength-shifting (WLS) fibre readout. Each superlayer, contained within an existing RPC module's aluminium frame, consists of two independent and orthogonal planes of scintillator strips (see Fig. 10). The scintillation light will be read by Geiger-mode photo-diodes (GPD) at one edge of the strip.

4. Summary and conclusions

B factories have proven to be excellent facilities to explore flavour physics. They have shown a reliable long term operation and were constantly improving their performance. By a major upgrade of the KEKB accelerator from 2009 to 2012, we plan to build the SuperKEKB, a next generation of a B factory with the luminosity which is up to 50 times higher than the maximum KEKB luminosity.

Although the new spectrometer will be built by using parts of the Belle spectrometer, the SuperBelle is essentially a new project. Due to much larger backgrounds, most of the components of the existing spectrometer will have to be replaced. A new collaboration has been created to perform the upgrade and later operate the spectrometer. The first two open meetings of the new collaboration have been held in KEK, Tsukuba, in December 2008 and March 2009; further meetings are planned in July and November 2009. With the new SuperBelle detector we are already looking forward to the new, exciting future of flavour physics, complementary to the physics programme at the LHC.

References

- [1] Akeroyd A K *et al* Physics at Super B Factory 2004 *Preprint* arXiv:hep-ex/0406071
- [2] Browder T E, Gershon T, Pirjol D, Soni A and Zupan J 2008 New Physics at a Super Flavor Factory *Preprint* arXiv:0802.3201v2 [hep-ph]
- [3] Buchalla G *et al* 2008 *Eur. Phys. J. C* **57** 309-492
- [4] Kurokawa S and Kikutani E 2003 *Nucl. Instr. and Meth. A* **499** 1-7 (and other papers included in this Volume)
- [5] Abashian A *et al* 2002 *Nucl. Instr. and Meth. A* **479** 117-232
- [6] Abe K *et al* 2004 *Letter of Intent for KEK Super B Factory KEK Report* 2004-4 ed S Hashimoto, M Hazumi *et al* (Tsukuba: High Energy Accelerator Research Organisation (KEK)) (The document is also available on <http://belle.kek.jp/superb>)
- [7] Adachi I *et al* 2008 *sBelle Design Study Report KEK Report* 2008-7 (Tsukuba: High Energy Accelerator Research Organisation (KEK)) (*Preprint* arXiv:0810.4084v1 [hep-ex])