Technical Review of the CKM Proposal

Review held May 15-17, 2001
Report released May 24, 2001

Introduction

During the three-day review of CKM and KAMI, the Committee devoted one day exclusively to each experiment. In the morning of the first day, CKM proponents gave the talks listed in the appended agenda. The afternoon was spent in closed sessions, in breakout sessions to address specific issues, and in another open session. The evening of the second day, and the entire third day, were devoted to drafting and discussing this report and the companion report on KAMI, and to conveying overall conclusions verbally to the proponents. Due to the tight time constraints and the emphasis on key issues, the Committee did not have time to review several aspects of CKM, including almost all engineering issues.

Overall, the Committee believes that a plausible case was made that CKM could be successfully completed. The proponents have asked themselves numerous probing questions and performed convincing studies as a result. There remain some potential showstoppers (notably if they are unable to construct straw chambers which work in vacuum), and there are outstanding issues such as neutron-induced rates in the 25 tons of veto scintillator, and rates in counters in the beam. However, overall the Committee's impression of the design is positive. Particularly relevant for the physics measurement are redundancies that will allow background to be estimated in a convincing manner from the data.

Kaon Beam Line

The Committee leaves the issue of the RF separation to another review, and has focused only on possible backgrounds created by the beam line. The aperture of the vacuum pipe is about r = 125 mm in the last pair of quads just before the beam enters the UMS, while the maximum beam size there is σ_x = 45 mm; thus, the aperture is three sigmas which means that 0.3% of beam particles will hit the aperture in the Gaussian approximation. For the particle flux of 50 MHz, the interaction rate is then about 0.15 MHz. This is a small number compared to the 3 MHz of kaon decays occurring in the UMS region. However, the beam is not Gaussian and there may be a large amount of beam halo. The Committee recommends that a quantitative estimate of this rate be made with the beam profiles obtained from the simulation, and that collimation be studied to reduce beam halo.

The kaon beam ends in a beam dump cavity where a large amount of debris is generated. The Committee urges that an estimate of the effect of these backgrounds on CVP and HVS be performed.

Beam Time Stamp

The beam time stamp module for CKM is a fiber tracker composed of 16 cm long 1 mm diameter fibers. The fibers are oriented vertically after the first magnet for the upstream spectrometer. Although challenging to implement in the harsh 50-MHz environment, the Committee sees no reason why the technology described in the proposal using multi-anode PMTs cannot work. All the specifications seem to be attainable.

The purpose of the detector needs clarification. It can serve to measure both the time and the "x" position of the incoming kaon. This information, however, is also available from the UMS chambers and the kaon-RICH. Nevertheless, the Committee believes that the redundant measurement could be quite useful. The power of the detector ultimately might be to tag events in which multiple particles enter the detector. Backgrounds due to such multiple particles are not handled with sufficient clarity in the proposal.

UMS, DMS and KEAT chambers (Upstream Momentum Spectrometer, Downstream Momentum Spectrometer)

The design of the MWPCs that will be used in the UMS and KEAT systems in CKM is based on a design of chambers that have already been built and operated successfully in a high-rate environment in HyperCP. The expected rates in hit rates per wire are similar to those already experienced by the HyperCP chambers without large losses of efficiency. The final design parameters, such as the wire spacing, will depend on the final beam intensity. The baseline wire spacing in the proposal and the tolerance on the cathode planes is somewhat smaller than the HyperCP chambers, but it does not represent a significant technical leap.

The amount of material in the chamber systems has an impact on the overall performance of the experiment. The collaboration has investigated other options for the UMS detectors, but found that the use of either pixel or silicon strip detectors would have significantly increased the amount of material in the beam. The expected performance of the proposed detectors seems to be well matched to the requirements of the experiment.

The UVa group on CKM has built similar chambers for the HyperCP experiment and they have the expertise to complete the design and construction of these chambers and the associated front-end electronics. A prototype of the chamber and the new faster electronics based on the Penn chip used in the CDF COT has been proposed to address the remaining engineering issues.

DMS

The DMS chamber system in CKM is made of 4 planar straw drift chambers. These chambers will be operating inside the decay vacuum tank. This system represents an engineering challenge, particularly since no previous straw system has been operated in vacuum. (MECO has also proposed using straws in a vacuum.) Single straws have been tested in vacuum and the straws have been observed to stretch in length. This effect has to be taken into account during the assembly process. The leak rate of the straw seems to be manageable, extrapolating from the single straw tests.

Since the DMS straw chambers will be in the beam region, the center of each wire that extends through the beam must be deadened. The planned electroplating of the individual wires will somewhat complicate the production process.

A straw chamber prototype has been designed and construction is underway. The completion of the vacuum tests with this small 20-straw prototype is a very important milestone for the experiment. There is no satisfactory alternative to the straw system, since other options considered would place too much material in the decay volume. It is important that adequate manpower and resources be allocated to this project.

The DMS is a critical system for the detector and represents a technical risk. The team at Fermilab is small but extremely competent.

RICH Detectors

CKM incorporates two Ring Imaging Cherenkov (RICH) detectors that provide a redundant measurement of the decay kinematics for $K \rightarrow \pi^+ \nu \bar{\nu}$ events. One of these detectors, the Kaon RICH, is situated just upstream of the decay volume and measures the vector velocity of the incoming kaon. The other detector, the Pion RICH, measures the vector velocity of the decay pion. The Kaon RICH is filled with 0.7 atmospheres of CF_4 while the Pion RICH uses neon at one atmosphere as its radiator. In both cases the light is detected by an array of 1/2" PMTs.

The operating point of these detectors (i.e., the index of refraction) is chosen such that the variation of ring radius with momentum is large enough that a reasonably precise measurement of the ring radius yields a fairly precise measurement of the momentum. The resulting momentum resolution is comparable to the measurement obtained in the magnetic spectrometers. As is the case with most any practical device, the response functions of both the magnetic spectrometer and the RICH detector system have tails, but since they operate independently, these tails are largely uncorrelated.

In addition to this novel momentum-measuring role, the RICHes also serve as traditional particle identifiers, providing excellent rejection of beam pions and decay muons.

In general the design of the RICH detectors seems quite robust and well suited to the high-rate CKM environment. The Committee views reliance on conventional PMTs as a strength since these devices are fast, stable, and perhaps most importantly, time tested and well understood. Very similar detectors were built for the SELEX detector, which demonstrates the viability of the technique and provides a good point of departure for the design of the CKM RICHes, which must meet more demanding specifications.

While the Committee believes that the approach is basically sound, it notes a few areas where further investigation is warranted. In particular, the tails in the SELEX detector were measured, but their origin was not understood in detail. The Committee believes that it is important to do so since the understanding gained in the process may be of relevance to CKM.

Another area where a more quantitative understanding is needed is the effect of accidentals on the tails of the RICH momentum response. Presumably this can be studied in a straightforward way by overlaying hits from accidental events and running the pattern recognition algorithms.

In the breakout sessions, it became apparent that there is a tail in the missing mass response function of the RICH spectrometers. Further investigation suggested that the origin of this tail was not in the momentum measurement but rather in the angle measurement. Understanding this effect in more detail may point the way to improvements in the RICH design.

As noted, a strength of the CKM design is the nearly complete decoupling between the RICH and tracking spectrometer measurements. One way in which these systems are coupled, however, is that the RICH momentum measurement will need to rely on position information from the downstream tracker in order to obtain the correct field integral from the DMS magnet.

The Committee did not dwell on the design details of the RICH. It did note, however, that the choice of a sub-atmospheric operating pressure for the Pion RICH could lead to practical problems such as contaminant inflow. Moreover, the proponents should ensure that their design holds the index of refraction constant at a level consistent with the required momentum resolution.

CKM Photon Veto System (VVS, BIVS)

In CKM the photon vetoes play the crucial role of suppressing the dominant $K^+ \rightarrow \pi^+\pi^0$ ($K_{\pi 2}$) background. According to the CKM version 1 calculation, a π^0 rejection of about 1.6×10^{-7} is required to maintain the $K_{\pi 2}$ background at the few event level. Background studies have been done under the assumption of factorization: the effective branching fraction for a given background channel is obtained by multiplying the veto rejection power by the kinematic efficiency. The π^0 rejection needed by CKM is about a factor of ten larger than what has been achieved by the BNL E787 experiment. (CKM is at a much higher average energy, which helps in general, but backward-going photons in CKM can have a lower energy than in E787.)

The proposed design is 5mm scint/1mm Pb sandwich as used in E787. The veto must work in vacuum; this has already been achieved in KTeV. The mechanical construction follows the KTeV design. Fifty percent of the vacuum region downstream of the UMS spectrometer is filled by vetoes. This figure is a trade-off between veto coverage on one hand, and detector cost and construction issues on the other; before construction, an optimization study would be needed. (The Committee was told that a packing fraction greater than 85% would complicate construction.)

Activity induced by the beam upstream of the detector

Singles rates in the CKM detectors are estimated by tracking particles from the target using the GEANT package. The GEANT code was modified to read the same files used to read the same magnet positions and fields used to generate the optics by the TURTLE program. Particles in the target were generated according to Malensek distributions. Particles reaching CKM are mainly kaons (75%), with 16% of pions/muons and 9% of protons. Singles rates in the detectors are calculated to be dominated by kaon decays. The rate into the VVS is about 6-7 MHz for a visible energy threshold of 1 MeV. In the forward VS, the rate is calculated to be 12 MHz for a threshold of 30 MeV visible energy.

Fast and thermal neutron rate in VVS

Although the VVS follows the KTeV veto design, the operating conditions will actually be quite different in CKM with respect to KTeV. Thresholds in the KTeV photon vetoes were usually kept at about 100 MeV, whereas CKM aims to veto visible energy deposits of about 1 MeV. There was no data yet analyzed from KTEV to estimate the rate induced by fast or thermal neutrons in a hydrogen-rich detector such as the CKM VVS or BIVS. Any KTeV data that might exist should be so analyzed, and further ways to perform relevant measurements (for example the response of the VVS to fast neutrons) should be explored.

(Some data were collected in KTeV during a one-day "pencil beam" run to address $K_L \rightarrow \pi^0 \nu\bar{\nu}$. The threshold on the photon veto was set to 5 MeV for the vetoes close to the DCH, 70 MeV otherwise.)

Occupancy in the DMS due to EM showers initiated in the VVS

GEANT is used to study the development of EM showers in the detectors. Secondary particles (electrons, positrons and photons) are tracked down to a 2 MeV cut-off. Particles from the EM showers leaking from the VVS system can spray the DMS. Low energy electrons and positrons can curl in the magnetic field and move backward. This can create some delayed hits in the vetoes leading to an increased random veto. The GEANT simulation could be used to study the effect but so far this has not been done. According to the proponents, the number of particles leaking from the veto is small with the result that a) the multiplicity in the DMS does not seem too large; and b) the low energy electrons do not appear to be an issue.

It was mentioned that lowering the GEANT tracking threshold to 100 KeV does not increase the veto efficiency significantly; sensitivity of rates to this threshold should be studied as well. (X-rays may be a concern).

Dead time due to VVS random veto

The rate in the VVS vetoes is expected to be about 7 MHz for a 1 MeV threshold. This is an average rate and the dead time calculated from it makes sense only if the 53 MHz ripple does not exceed 10-20%.

At the trigger level one vetoes energy deposits larger than 1 GeV in the VVS. The veto gate to be used in the trigger is about 15-20 ns. Off-line one should get 1-nsec timing from the scintillator and about 3 ns double pulse separation. The random veto will kill genuine signal events at about +/- 3nsec * 7 MHz ~ 4 % level.

The rate in the FVS is dominated by muons from kaon decays. A muon crossing the FVS deposits about 100 MeV of visible energy. The rate is calculated to be ~12 MHz. To avoid significant random veto, the threshold to veto photons in FVS cannot be less than several hundred MeV.

Inefficiency induced by pile-up

Pile-up in the VVS counters may lead to inefficiency to detect low energy photons in the wake of large pulses. A maximum base-line restoring time of about 40 ns is assumed. The maximum rate for a PMT is about 400 kHz for a 1 MeV visible energy threshold. The probability for the 1 MeV photon to pile-up on the tail of the preceding pulse and be missed is: 400 KHz *40 ns = 1.6 %. This is a small inefficiency compared with the CKM-required inefficiency of less than 40% for photons below 40 MeV.

Read-out considerations

Each veto is composed of two longitudinal segments. Each segment is formed by 39/40 scintillating tiles read out via scintillating fibers. Odd and even tiles are coupled to different PMTs to provide redundancy. About 2,200 PMTs must be read out. Time history from each PMT (about 200-300 ns) is recorded by means of multi-hit TDCs (to be developed). Pulse-height is recorded by transient recorders (QIE) similar to the ones used in KTeV and CMS. Pulse height data will be recorded on a small time region nearby the trigger to avoid too large data volumes.

The QIE employed in KTeV needs two modifications to effectively work in the VVS application: a) It must work with un-bunched beam; this should not be a problem. b) Owing to the very short VVS pulses (FWHM 7.4 ns) the QIE sampling frequency should be at least 100 MHz, about twice as large as in KTeV. If the QIE cannot work at 100 MHz, two 50 MHz QIE per channel could be foreseen, one sampling on the clock and the other on the clockbar.

The CKM collaboration has thought a lot about the VVS system, much more than the review committee can possibly have done. During the main session and the breakout session, committee members were not able to ask a question that CKM collaborators had not at least thought about. No showstoppers were identified. However, there are some areas of concern and risk factors:

In the Committee's estimation, the main risk factor having to do with the photon veto systems is the estimated singles rates down to 1 MeV energy threshold. The optimal energy threshold is a three-way trade off involving accidentals- or pileup-induced dead time or inefficiency (if the threshold is too low) and low energy photon inefficiency (if the threshold is too high), and kaon flux. Singles rates were calculated by a GEANT simulation of the beam line down to a particle energy of 2 MeV. If the singles rates turn out to be higher than estimated, the experiment may be forced to raise its photon veto energy threshold. What will happen to the sensitivity of the experiment if they are forced to raise the energy threshold from 1 MeV to 2, 5, or 10 MeV?

One area of uncertainty that was mentioned several times throughout the review is the lack of an estimate of the singles rate of soft neutron interactions, which is not included in the GEANT simulation. It is probably true that a charged beam has fewer soft neutrons than a neutral beam, but neutrons are not obviously negligible. The Committee recommends that the proponents investigate whether there are nuclear physics codes that are able to calculate the scattering and propagation of neutrons from high energy down to thermal energies. The Committee also recommends that the proponents measure the response of their proposed veto counters to fast and thermal neutrons using a radioactive source of known strength.

The second main area of risk is the estimated photon veto counter inefficiency curve vs. photon energy. This curve is relatively well measured in the middle energy range, where there is data from E787. However, it was stated by the proponents that the hardest events to veto are the ones involving highly asymmetric π^0 decays with one low-energy and one high-energy photon. In these regions there is no direct measurement of the photon inefficiency. The worst problem exists for the high-energy part of the curve, where there is no way to measure the photon infancy short of doing an experiment such as CKM or KAMI. The collaboration has made an argument based on estimating all processes (e.g. photo-nuclear effects) that can lead to a loss of detected photons. This argument leads to an acceptably low intrinsic photon inefficiency, but there is a danger that there are photon loss mechanisms that haven't been considered.

The experiment is also worried about more mundane sources of inefficiency, such as dead phototubes. To this end, they are worrying a lot about monitoring. This is good.

Another area of concern involves timing. The experiment is planning on using a +-3 ns time window on the photon veto counters offline. Is this large enough? Are there background processes that generate late hits in the veto counters and can only be rejected using these late hits? Late hits could come from slow-moving particles such as neutrons, long-lived unstable nuclei, or particles that reach the photon veto counters via indirect or circuitous paths.

A final area of concern is the geometry of the VVS, which has gaps that particles can escape through. The proponents explained that the $K_{\pi 2}$ background has an energy-angle correlation such that only very low energy photons, where the veto counters are anyway inefficient, have a large enough angle to escape through the gaps. Since the $K_{\pi 2}$ background has been simulated with the gaps, this argument shows that the $K_{\pi2}$ background would not be significantly reduced by closing the gaps. The Committee learned, however, that simulation of the interaction backgrounds did not use a model of the apparatus that included the gaps. Furthermore, particles from these backgrounds may not have the same energy-angle correlation as $K_{\pi2}$. Therefore, these backgrounds need to be re-estimated with the correct geometry.

Exit Time Plane and Conversion Veto Plane

The technology for both of these devices is the same as that of the Beam Time Stamp Module (BTSM).

The Exit Time Plane (ETP) is not described in the proposal. The purpose of the module is less clear than the BTSM. Whereas the BTSM could be useful to tag interesting background events, the Committee does not yet understand the purpose for ETP in terms of understanding backgrounds.

The Conversion Veto Plane (CVP) seems essential to veto photons that convert in the pion RICH. The electron-positron pairs from this will be swept out by the BM109 magnet, and must therefore be detected before the magnet. It should be kept in mind that this veto must work in the presence of a 50 MHz (perhaps somewhat less due to decays) beam going through the detector. It appears that the acceptance loss due to this veto is not in the efficiency table. After the Committee's comments the proponents pointed out that the inefficiency in the CVP may not be debilitating since they could detect overlapping kaons in the KEAT and point to the region in the CVP that cannot be used for a veto. The proponents also point out that the veto time-window in this detector could be quite narrow. However, the Committee believes that it could not be better than +/-3 ns because of the length of the fibers as well as scintillation time constant in the fibers. The proponents have agreed to answer the following questions:

1) What is the pointing accuracy for a beam particle in the CVP using the direction and position obtained in the KEAT?

2) What is the effect on the background level if there is no CVP?

It might be necessary to simulate carefully the design of the inner edges of the muon veto and the conversion veto plane. The inner edges of the muon veto might be ultimately used to reject photon conversions.

Muon veto

The muon veto system is necessary to reject background from $K^+ \to \mu\nu$ and $K^+ \to \mu\nu\gamma$. The CKM collaboration set the design specification to reject all but 1 in 10^5 muons while retaining 95% of pions. (This is the reverse of the usual muon system used in HEP.) This would yield 0.1 background events from these modes, so in fact a muon vetoing inefficiency of

10^{-4} would appear adequate. The proponents noted, however, that a better inefficiency serves to give a cleaner sample of pions to check out the pion RICH.

The design (segmented iron-scintillator) appears reasonable. A smaller prototype was built and tested at the Protvino U-70 accelerator in November 2000. With the present analysis, muon veto inefficiency of 5×10^{-6} is achieved while retaining 87% of pions. With the real (longer) MVS, slightly relaxed cuts, and some modest algorithm improvement, it is reasonable to expect the CKM MVS to conform to the above design specification.

Trigger/DAQ Detectors

From the proposal and from discussions during the review it is apparent that the proponents have not devoted as much attention to the DAQ system as they have to other aspects of the experiment. This is appropriate at this stage since it is more important to validate the basic principles of the experiment than it is to work out technical details. The proponents presented a rough statement of the requirements for their system and made a plausibility argument that these could be met without pushing the state of the art in DAQ design.

However, digesting the projected 220 kHz Level 1 trigger rate is a difficult task, especially given the stringent requirements on maintaining the integrity of the data ("broken events" at the 10^{-3} level, which would be a nuisance in many experiments, would be fatal in CKM).

In addition, the TDC requirements for CKM require custom development, which history has shown can be costly and time-consuming. A similar development effort may also be needed for the pulse height recording circuitry. (The proponents say they are less concerned with the former, for which they say chips are already available. The latter requires a new QIE being developed for CMS.)

One obvious way of reducing the load on the DAQ is to reduce the Level 1 trigger rate (currently estimated to be 220 kHz). Conversely, a higher-than-expected Level 1 rate will make it that much more difficult to construct a suitable DAQ system. Either way, one concludes that it will be important to study the trigger in some detail. Doing so at an early stage may lead to alterations in the design of the detector systems that facilitate efficient triggering.

Signal acceptance calculation

The CKM collaboration has updated a number of signal and background efficiency calculations since v1.0 of the proposal. The presentation of the results has led to some confusion, since some results are retained from v1.0. While the comparisons with v1.0 are of interest (in particular to confirm that two background calculations give consistent answers), it would be very useful to have a comprehensive summary of the current expectations. For example, the number 13% in the text on p. 217 should be reconciled with other numbers on that page and elsewhere.

Backgrounds

The proponents have presented an extensive discussion of the potential backgrounds to the $K^+ \to \pi^+ \nu \bar{\nu}$ signal. The most serious backgrounds are from $K^+ \to \pi^+ \pi^0$ decays, with backgrounds arising from scattering in the material of the detector following close behind. Backgrounds involving muons are estimated to be less serious owing to the combined rejection power of the pion RICH and the MVS. More esoteric backgrounds involving such things as K_L's from nuclear interactions and accidental combinations of beam and decay particles were also estimated to be small.

The Committee did not find flaws in the background studies that were presented, although the treatment of accidental backgrounds seems somewhat cursory and should be expanded to include all plausible combinations (final states). It is also vital that the scattering backgrounds are closely scrutinized since the underlying hadronic physics is subtle and may not be properly modeled.

Appendix I

Technical Review of the CKM and KAMI Proposals

May 15-17, 2001

Committee Membership

R. Cousins, UCLA (Chair)
A. Ceccucci, CERN
M. Diwan, BNL
H. Greenlee, Fermilab
D. Marlow, Princeton
P. McBride, Fermilab
H. Yamamoto, Hawaii

Appendix II

Technical Review of the CKM and KAMI Proposals

May 15-17, 2001

CHARGE

The Committee should perform a technical review of the CKM and KAMI experiments addressing concerns related to the proposed techniques and designs of the experiments and their feasibility for accomplishing the physics goals.

• Can the experiment accomplish the measurement?

• Are there particular problems that might compromise the measurement or proposed cost/schedule?

• Are the method and techniques to be used for measurement sound and realistic?

• Are the proposed beam characteristics and intensity adequate for the measurement?

The Beams Division recently held a review of the CKM RF-separated beam, but the report is not yet available. A comprehensive cost review will take place in May led by the Particle Physics Division.

Appendix III

Technical Review of the CKM Proposal
May 15, 2001

8:30	Closed Session		
9:00	Introduction	Peter Cooper	(15 min)
9:15	Tracking		
	UMS	Craig Dukes	(15 min)
	DMS	Hogan Nguyen	(15 min)
	RICHes	Peter Cooper	(15 min)
10:00	Vetos		
	Photon / Interaction	Bob Tschirhart	(30 min)
	Muon	Vladimir Molchanov	(15 min)
10:45	Coffee		(15 min)
11:00	Simulations		
	Signal acceptance	Erik Ramberg	(30 min)
	Backgrounds		
11:30	What's Next?		
	Simulations	Erik Ramberg	(10 min)
	Prototypes	Peter Cooper	(20 min)
	electronics / DAQ		

Afternoon: closed sessions, breakout sessions, and open discussion with proponents