Charged Kaons at the Main Injector

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A Proposal for a Precision Measurement of the Decay $K^+ \to \pi^+ \nu \overline{\nu}$ and Other Rare K^+ Processes at Fermilab Using the Main Injector

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SUMMARY

We are proposing here an experiment to measure the branching ratio of the ultra-rare charged kaon decay $K^+ \to \pi^+\nu\overline{\nu}$ by observing a large sample of $K^+ \to \pi^+\nu\overline{\nu}$ decays with small background. Our physics goal is to measure the magnitude of the Cabibbo, Kobayashi, Maskawa matrix element V_{td} with a statistical precision of about 5% based upon a ~ 100 event sample with total backgrounds of less than 10 events. This decay mode is known to be theoretically clean. The only significant theoretical uncertainty in the calculation of this branching ratio is due to the charm contribution. A 10% measurement of the branching ratio will yield a 10% total uncertainty on the magnitude of V_{td} .

The experimental technique we are proposing is decay in flight in a $\sim 22\,\mathrm{GeV/c}$ RF separated K^+ beam with a kaon flux of 30 MHz and a purity of higher than 70% K^+ generated with about 5×10^{12} 120 GeV/c protons per spill from the Main Injector. The detector will have redundant measurements for both the K^+ and π^+ with conventional high rate magnetic spectrometers and velocity spectrometers based on phototube ring imaging Cherenkov counters for each particle. A hermetic photon veto system capable of rejecting π^0 decays with an inefficiency less than 1.6×10^{-7} and a muon range stack capable of rejecting μ^+ with an inefficiency less than 1×10^{-5} are also required. The expected signal acceptance of this apparatus after all cuts will be $\sim 2\%$. A data collection period of 2 years should yield a 100 event signal over a background of less than 10 events assuming a branching ratio of 1×10^{-10}.

This new experiment is known as "Charged Kaons at the Main injector", or "**CKM**".

This document is the second edition of this proposal. The first edition was submitted three years ago (April 15, 1998) and resulted in the approval of an R&D project to assess the technical feasibility of the experiment. The results of these studies are reported here. Using prototypes, test beam studies and simulations qualified by data we have verified the assertions we had made in the first edition. Initial prototypes of superconducting RF cavities have been procured and tested at superconducting temperatures. A first full 13 cell cavity is being fabricated now. The π^0 inefficiency of 1.6×10^{-7} is achievable using 1 mm lead, 5 mm scintillator photon vetoes based upon a combination simulations at low photon energies and estimates based upon data in the high energy regime. A muon range stack prototype was tested in a muon test beam at IHEP Protvino. It achieved the required μ^+ inefficiency less than 1×10^{-5}. We have recently completed a full hit level simulation of both the separated beam line and the complete detector. The first and most straightforward reconstruction and analysis of these simulated data already achieve kinematic background rejection levels supportive of what was quoted in the first edition of this proposal

The only significant change to the experiment has been the adoptions of fine pitch, high rate, multi-wire proportional chambers as the detectors used to track the 50 MHz beam. The advantages over the silicon strip detectors which we first proposed are significantly improved time resolution and ease of readout while maintaining a very low level of material in the beam. The University of Virginia group which successfully designed, built and operated such a chamber system in *HyperCP* has joined CKM and will lead this effort. In total the collaboration has grown from 19 physicists at 4 institutions three years ago to 46 physicists at 9 institutions today. This includes a group

from our sister experiment E949 at Brookhaven. E949 and CKM have joined forces. Several members of CKM from Fermilab and IHEP have joined E949 with the goal of proceeding in a programmatic fashion from the one event signal observed by E787 at Brookhaven through a 5-10 signal events expected in E949 using an upgraded E787 apparatus to CKM's 100 events with a significant measurement of the branching ratio for this ultra-rare decay mode.

The rest of the world of kaon physics has vigorously evolved in the past three years. There are now two approved and funded experiments to observe and measure the branching ratio of $K_L \to \pi^0 \nu \overline{\nu}$; KOPIO at Brookhaven and E391a At KEK, two approved extensions of the NA48 experiment at CERN to make high sensitivity studies of K_S^0 and K^+ decays and planned programs of high sensitivity kaon studies at both IHEP Protvino and at the new Japanese Hadron Facility (JHF). This community of kaon physicists is now poised to perform a new generation of kaon experiments that can quantitatively challenge the Standard Model. The CKM experiment will be a key player in this world-wide program.

Contents

List of Figures

List of Tables

1 Introduction

We are proposing here an experiment to measure the branching ratio of the ultra-rare charged kaon decay $K^+ \to \pi^+\nu\overline{\nu}$ by observing a large sample of $K^+ \to \pi^+\nu\overline{\nu}$ decays with small background. Our principal physics goal is to measure the magnitude of the Cabibbo, Kobayashi, Maskawa matrix element V_{td} with a statistical precision of about 5% based upon a 100 event sample. This measurement will play a critical role in testing the Standard Model hypothesis that the sole source of CP violation in nature resides in the imaginary parts of the V_{td} and V_{ub} Cabibbo, Kobayashi, Maskawa matrix elements. Attacking this question in the kaon sector is both experimentally and theoretically independent of the ongoing programs to measure these same parameters in the B meson sector. Each sector provides an independent test of the Standard Model description of CP violation. Both must measure the same parameters for that description to be correct. Such a parallel approach is critical to confirm, with confidence, both the Standard Model description of CP violation and the veracity of the individual measurements.

The $K^+ \to \pi^+\nu\overline{\nu}$ decay mode is the theoretically cleanest laboratory in which to measure the magnitude of V_{td} [1]. The calculation of this decay rate is relative to the $K^+ \to \pi^0 e^+\nu$ decay mode. This cancels uncertainties due to the hadronic structure of the $K^+ \to \pi^+$ X transition. Long distance contributions to this decay have been calculated [2] [3] [4] [5] to be negligible. The only significant uncertainty in the relationship between the branching ratio and $|V_{td}|$ is a small contribution from the charmed quark which depends upon the poorly known charmed quark mass.

Evidence for this decay mode has recently been published [6] by experiment E787 at Brookhaven National Laboratory (BNL). They reported the observation of one event with an expected background of 0.08 ± 0.03 events and quote a branching ratio of $[1.5^{+3.4}_{-1.2}] \times 10^{-10}$ [6]. This branching ratio is consistent with the current prediction of $[0.77 \pm 0.21] \times 10^{-10}$. The next important step is a measurement of this rate with sufficient precision to quantitatively challenge the Standard Model interpretation of the source of CP violation. That is the goal of this experiment. The design of our experiment has benefited enormously from the BNL E787 achievement, which has shown that all physics backgrounds to the 10^{-11} level have been identified and can be controlled.

The challenge of this measurement then is clearly experimental. A signal of 100 events if the branching ratio is at the predicted level requires that the apparatus control all backgrounds to less than the 10^{-11} level. In order to achieve an order of magnitude increase in sensitivity per year of data taking while maintaining excellent control of all backgrounds requires an apparatus with much higher rate capabilities than has been achieved in the BNL experiment. This leads us to propose a decay in flight experiment in contrast to the stopped kaon technique used at BNL. This new experiment is known as "Charged Kaons at the Main Injector", or "**CKM**".

In addition to the paramount goal of measuring the $K^+ \to \pi^+\nu\overline{\nu}$ branching ratio we also plan a series of other measurements of rare charged kaon decay properties using the CKM apparatus. The high rate capabilities and redundant measurement capabilities of the CKM spectrometer will make it well suited to such a program of measurements.

9 Siting and Conventional Construction

9.1 Siting Constraints

The configuration for the CKM experiment utilizes 22 GeV kaons from a Superconducting RF Separated beamline, designed to deliver a flux of 3×10^7 positively charged kaons in a 1 second spill. In the design of this proposal, the detector requirements as well as the beam requirements are developed to a stage that allowed consideration of the location of the experiment. Consideration of existing facilities in the laboratory, or the need to design new facilities, have been studied as well, keeping in mind that physical constraints of the experiment and beam are not expected to change significantly in the near future. With the uncertainty of the laboratory schedule, other commitments of facilities under consideration, and priorities of the laboratory management, this narrative makes no assumptions about the availability of present or future facilities. We have concentrated on the most compatible domain of existing territories in the designated Meson area.

There are four general areas of consideration, and in some cases constraints. These areas include the experimental geometry, a general description of the Meson beamline sites, preliminary ideas on construction, and initial thoughts on the environmental assessment. A more detailed analysis including more information on the muon backgrounds and shielding, are integrated into this proposal. It is important to state that one of the major fixed target areas using the Main Injector beam at Fermilab considered for future operations is the Meson area. A scaled layout of the Meson area is shown in Figure 153. The design of the beam also poses a constraint. There are three general sections located after the target and the momentum selection, namely a RF separator section, a 'clean-up bend section' of the beam to keep the secondary muon flux away from the detector, and the experimental detector region. The need for this final bend and the cost in muon contamination are discussed in Section 4.

9.2 Geometry Constraints

In evaluations concerned with siting the relatively recent KTeV facility, a number of options were considered. Primary among the constraints regarding utilizing existing buildings was the size and shape of the detector. A long detector, large decay region, and increased beam intensity resulted in a recommendation that led to construction of a new facility, rather than the use of an existing experimental hall. This result was also highly coupled with the upgrade of an existing beamline. The proposed CKM experiment has similar requirements for the detector apparatus, and some unique requirements for a new beamline that uses Main Injector primary protons, cryogenic and RF equipment, and controls.

9.3 Superconducting RF Beamline

A number of beamlines have operated in the Meson area over the past 28 years, including beams utilizing superconducting elements. Our present effort must couple the efficient extraction and transport of the Main Injector primary beam with the location and operation of the superconducting RF separated secondary kaon beam (SCRF). The superconducting RF separated beam has a number of features that influence the design, operational efficiency, and the possible location of this beam in existing areas. Existing locations take into account the detail beam design and constraints imposed by the requirements of the CKM experiment.

To meet the experimental requirements, the beamline should deliver a kaon rate of 30 MHz using 5E12 protons per pulse from the Main Injector accelerator. The RF separated secondary beam is expected to separate out a pure Kaon flux over all other hadrons. The beam is approximately 210

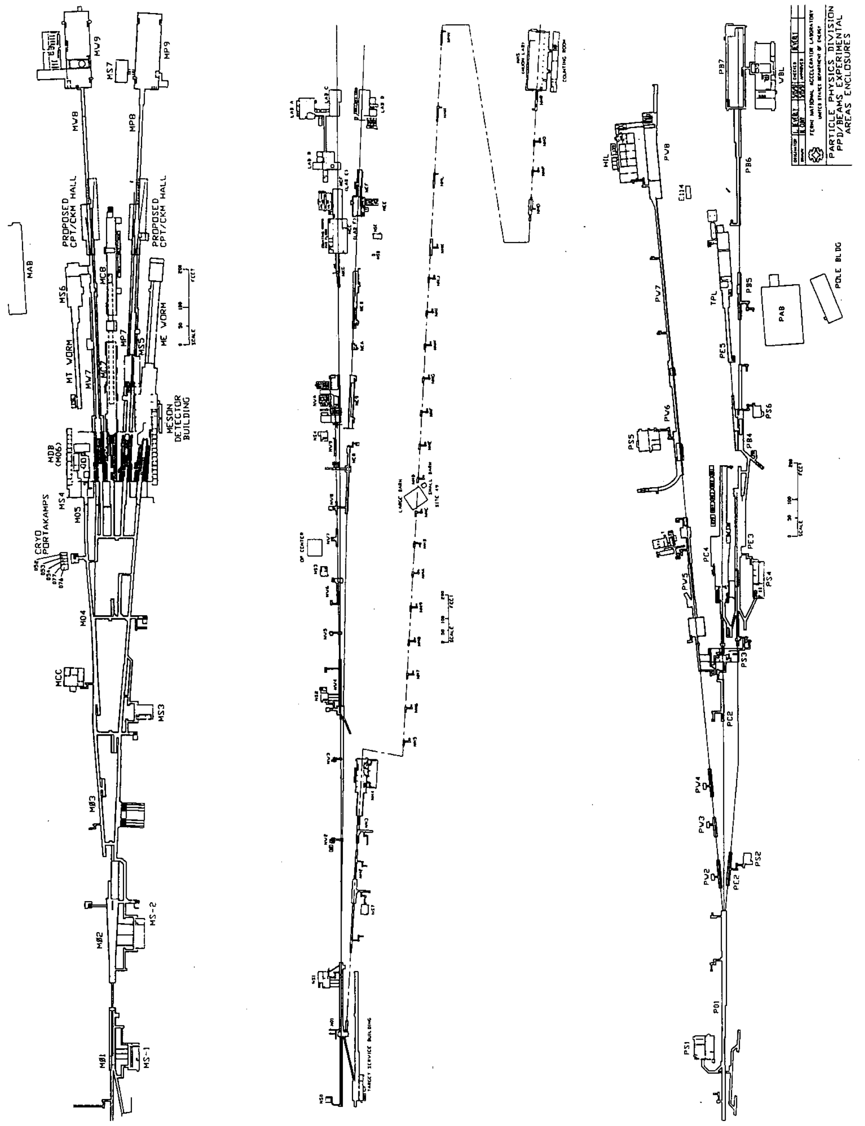

Figure 153: Fixed target experimental areas. The Meson Area is on the left.

meters long characterized by an initial targeting and momentum selection section, followed by two superconducting RF deflector stations nearly 85 meters apart, followed by a beam plug device to absorb the unwanted particles after separation, and a final focusing section for transport to the CKM detector.

Unlike conventional fixed target beamlines, this beamline requires superconducting RF cavities, and the associated cryogenic equipment to support and operate the cavities. An engineering sketch of the proposed cryostat units showing the configuration of two half meter RF cavities is presented in Figure 28. A station consists of 3 meters of RF cavity and contains three cryostats per station. The frequency of the cavities (designed for 3.9 GHz), and the separation between the RF stations is a constraint chosen to fit the particle RF phase requirements of the beam design. Flexibility in the properties of the beam is expected if the design goal of $\sim 5MV/m$ in cavity field strength is not met or exceeded. These particular features, along with the location of the target station and space needed for the final focus and clean-up bends, restricts the location of this beamline. The enclosure space around the RF stations must be sufficient to include the controls equipment and piping for the liquid cryogen necessary to keep the RF cavities at cryogenic temperatures.

9.4 Meson Area Sites

There are a number of historical beamlines in the Meson area, including in some configurations, MP (meson polarized beam), MT (meson test beam), ME (meson east beam), MW (meson west), MC (meson center), and at one time MB (meson bottom). Not all of these beamlines are compatible with the expected new fixed target configuration without extensive redesign and modification. Since the facility requirements for the RF separated beam and the proposed CKM experiment are presently highly developed, some of the possible sites in the Meson area were deemed not feasible, due to estimated large capitol cost required to prepare these areas for Main Injector beam. Although not exhaustive, we have concentrated the limitations to a few areas of consideration, namely the connection to the Switchyard 120 design (SY120) [193], existing enclosures that would need the minimum of modification, an area for the target station, the length of an existing beamline, and in some cases a modified existing experimental hall that could accommodate the CKM experimental apparatus.

9.4.1 MP Beamline

The MP beamline will receive primary beam from the Main Injector through a reconfigured switchyard, included in the Switchyard 120 Project (SY120). This project is initially applicable to other beams mentioned above, but it is important to note that the preliminary SY120 design extracts beam to the Meson area, then later provides beam to the MT area, primarily. Over a year after this work, the three way split will be revised and then provide beam to three different areas. The impact of this current SY120 project plan is not expected to impose further constraints on the current proposal for CKM. The beamline enclosure extends from far upstream of the Meson Detector Building (MDB) near the M05 cross over tunnel enclosure, and runs downstream to the MP9 Experimental Hall, as shown in Figure 153. This region can accommodate either an upstream or downstream scenario for the facility, (each length in excess of 400 meters). Existing beam pipe is also in place from the switchyard to MDB, (for all current beamlines). Portions of these spaces are sufficient for the expected 60 elements that make up the beamline. Cross sections of various tunnels may be sufficient (in the current configuration), in regions where superconducting RF cavities cryogenic equipment can be placed. This equipment is unique to some beamlines, but similar in scope to the usual elements of magnets, collimators, and monitoring devices normally found in beamlines.

Precise locations depend on the position of the target station, elevation above the existing floor, and a final bend for muon cleanup. Figure 154 presents a sketch of the Kaon facility overlaid on existing areas of the ME beamline and MP Experimental Hall. Both the downstream region and the upstream region utilize existing space and tunnels. Although some of the additional required enclosures exist, some modification of them will be required.

9.4.2 ME Beamline

A region near the MS3 service building cross-over to the MDB totals approximately 200 meters. Although in some areas, the cross sections of the tunnels are smaller than the MP tunnels, there is continuous tunnel into the MDB an beyond. An additional 100 meters is required for the detector, as well as the needed detector environment. The area downstream of the MDB is known as the ' WORM '. Previous experiments have been located and operated in this area. However, an engineering assessment would be required to determine the modifications needed to construct the CKM experiment in this area. The proposed configuration of the experiment does not fit in the MDB. This condition supports a proposed location for the target building, RF separator section, and subsequent beam section and experimental hall downstream of the existing Meson detector building.

9.4.3 Experimental Apparatus

The geometry for the CKM experimental apparatus is shown in Figure 42. In its current design, the detector portion of this apparatus is approximately 100 meters long, with varying cross sections and a cross section limit of approximately 3 to 4 meters. The major portions of the apparatus include an upstream magnetic spectrometer including a kaon RICH counter; a vacuum decay region, which includes a downstream magnetic spectrometer system; and a downstream pion RICH counter, muon system, additional veto system, and beam dump. Preliminary engineering design of the vacuum system indicates a cylindrical geometry, about 40 meters long, with approximately a 1.9 meter diameter cross section for the vacuum tank. Completely surrounding this tank are ports and connections along the entire length (at periodic intervals) for the vacuum veto photomultiplier tubes. This geometry constrains the apparatus to be centered on the beam, but well above the floor level in order to access the surrounding detectors and match the existing elevation of the Meson area beamlines. The proposed design of the vacuum veto modules is shown in Figures 78, 79. Electronics equipment space for the four plane X-Y-U-V drift chambers is also needed in this area, as well as numerous cables connecting to all of the instruments. Since many detector components are inside the vacuum, view ports will be required for drift chamber surveys, as well as sufficient transverse space and distance conducive to laser surveys and laser position monitoring. The vacuum section also includes straw tubes surrounding and bordering a magnetic field region. This section will include numerous sheets of lead and scintillator. Due to the massive and delicate nature of the instrumentation for many of these elements, a crane is required, capable of off loading and lifting the detector elements into position. This crane is also a safety constraint (and large detector units are expected). Experience gained from operating the KTeV experiment, and analysis of KTeV data, suggest that a reliable temperature controlled environment is required to maintain stability.

Figure 155 shows a 'scaled sketch' of the superposition of the CKM detector and the existing MP9 experimental hall. This is not an engineered, precise drawing, but a suggested match to the constraints already discussed in this proposal. Since the beam dump does not have significant instrumentation requirements, placing or burying this element beyond the downstream wall of the present building does not create a significant technical difficulty, but optimizes an adjustment in

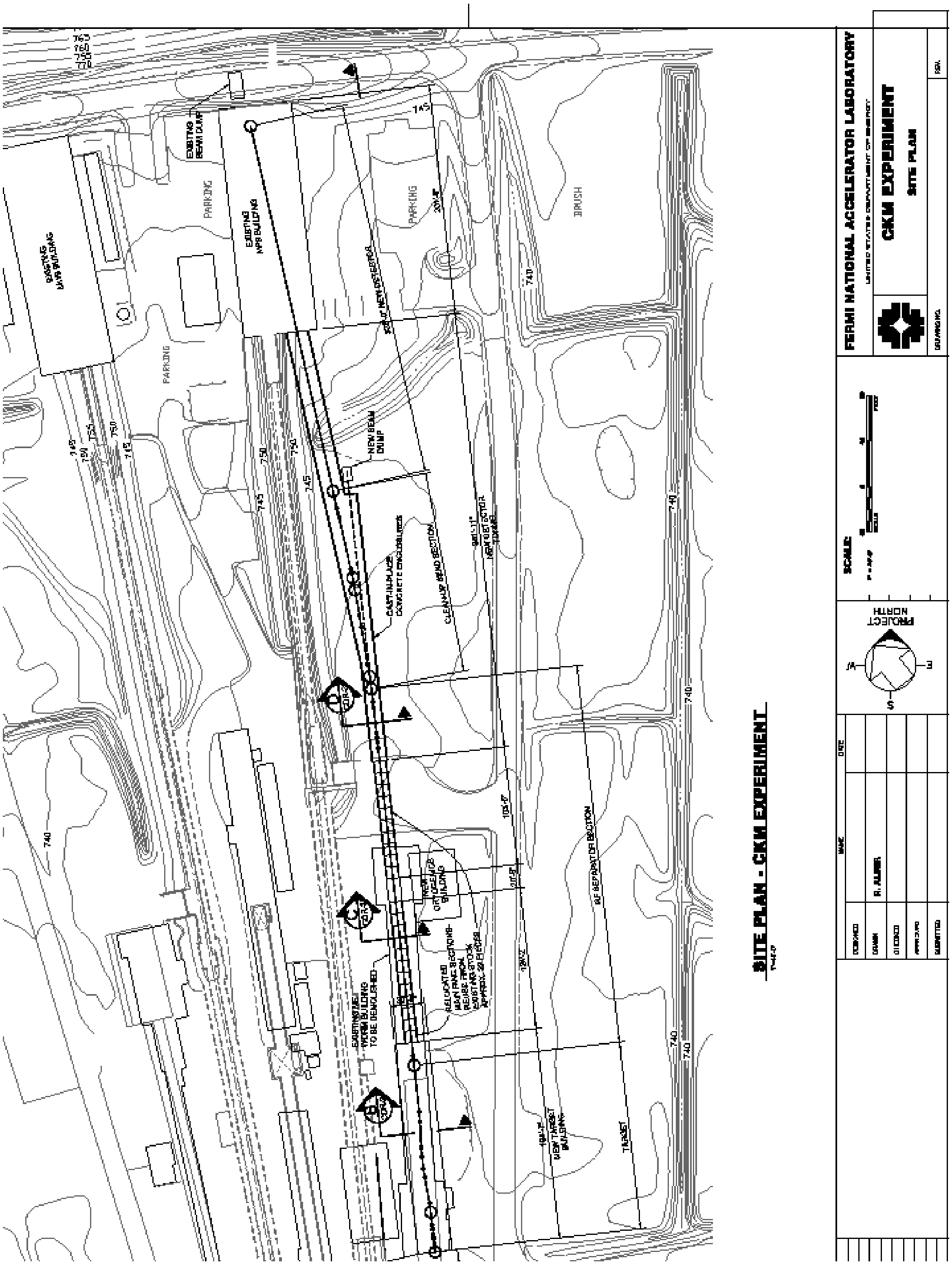

Figure 154: The MP9 experimental hall configuration.

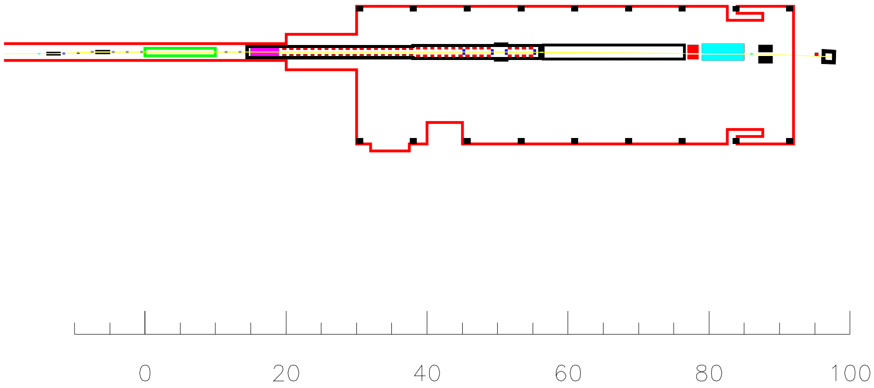

Figure 155: The CKM detector and the existing MP9 experimental hall. (meters)

position of the overall length. The upstream detector elements also fit within the existing beamline tunnel. The upstream tunnel-enclosure area cross section is approximately 3.2 meters diameter, and the far upstream beamline tunnel leading to this hall is about 2.9 meters diameter. Of course, a detailed engineering assessment of this experiment-hall configuration (or alternatives) would provide a better understanding of the possibilities, but with modifications this possible location seems to fit many needs of the CKM experiment detector. However, the competition for existing property is also a factor for consideration in the optimal use of laboratory resources. As a result of this competition, the CKM experiment also considers alternative locations for housing the experimental apparatus, requiring a new experimental hall. We have been explicitly asked by the Fermilab Directorate to consider a new experimental hall which leaves MP9 for other purposes. We discuss this option below.

9.5 Construction

It is expected that some construction is required for areas of the beamline, driven by the physical constraints of the beam design, and possibly radiation shielding requirements. Design characteristics, beam yields, and associated muon background fluxes studies have been extensively simulated. A combination of operations may be employed to reduce the muon background at the experiment, but also measures will be considered to contain the radiation field generated from muons all along the beamline. The bend in the beamline after the separator beam dump will limit the direction of the muons produced from that dump source.

9.5.1 Target Enclosure

All configurations of the beamline include the design and construction of a target station. A preliminary lay out of a target station that fits the current beamline design is shown in Figure 156. A detailed model and analysis of this target pile is discussed elsewhere. [134] The target, magnetic elements, and shielding portions fit in an area 147 feet long by 25 feet wide. This configuration is expected to maintain effective shielding for primary beam at 120 GeV, 3 sec repetition rate, 5e12 ppp, resulting in a residual dose of no more that 100 mrem on contact outside of the immediate shielding wall after 30 days operation and 1 hour cool off.

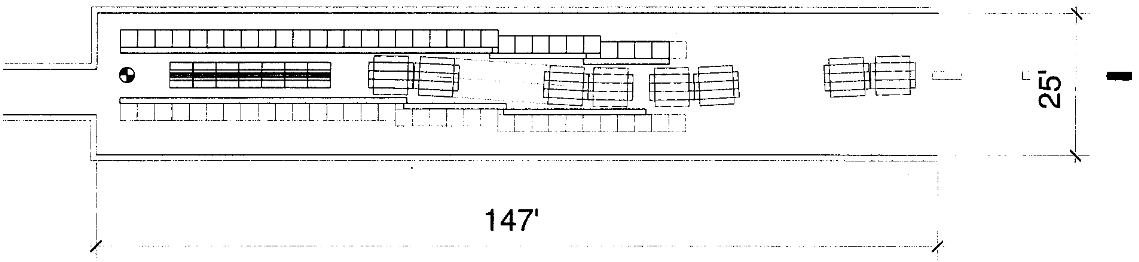

Figure 156: Target enclosure.

One of the reasons for either re-configuring or redesigning a new target station is adherence to any new regulations concerning radiation shielding, particularly ground water contamination shielding. The configuration for the target station presented here is part of a beamline that is approximately 210 meters long, stretching from the target to the last magnet element of the beamline before the detector. (Note that the detector is an additional 100m long). Choosing the location of a current existing target station is problematic at best, since the length of the beamline is a constraint and adding more distance from the end of the beamline to the detector reduces the expected flux of kaons at the detector due to particle decay, and increases muon flux. For example, placing the target station in the Meson Detector Building would add nearly 40 meters to the decay length for the beamline assuming the detector was located in the nearest available existing experimental hall in the MP beamline. Therefore the proposed location for these facilities is a new target station in the ME beamline located to minimize loss of kaons from particle decay, maximize kaon beam purity and optimize the elements for radiation shielding.

9.5.2 Experimental Hall

It should be pointed out that the construction of a new experimental hall similar to the MP9 hall would cost approximately $2M, according to a current FESS estimate of $150/square foot. This estimate does not include EDIA, administrative contingency, or any upgraded power for experimental equipment, etc. This particular cost helps compare options such as using (and modifying if necessary) an existing experimental hall, building a new facility, or limiting the experimental requirements to fit available real estate.

A configuration is presented in Figure 154 which shows construction of the target hall in the extension downstream of the MDB, a secondary beamline incorporating new enclosures and existing relocated main ring tunnel sections, matching into connecting space with the existing MP9 facility. This configuration also requires modification of the ME worm and some modification of the MP9 experimental hall. It should also be pointed out that this configuration does not impact other possible experiments located in the MDB. An alternative proposal is shown in Figure 157, which does not reflect utilization of the MP9 facility and illustrates the location of a new experimental hall, previously discussed.

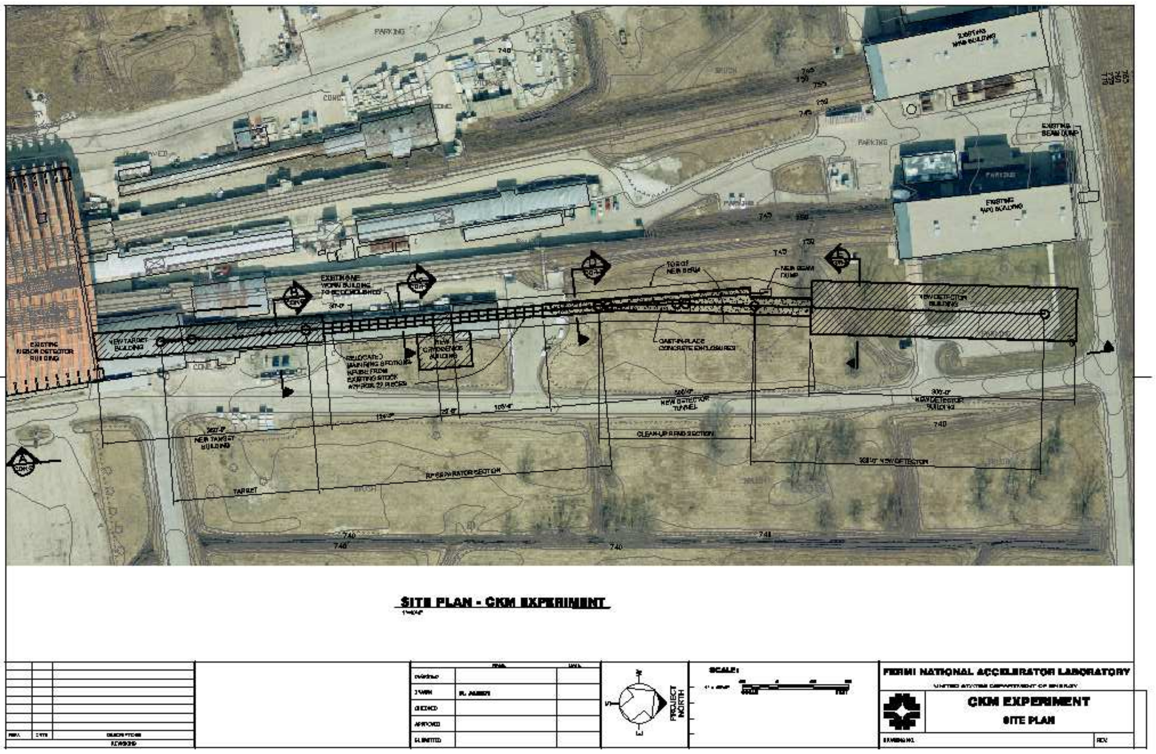

Figure 157: A new experimental hall configuration.

9.6 Environmental Assessment

Since the proposed action for siting the CKM experiment is in an existing research area, more general considerations for the required assessment will probably take precedent. These concerns include modifications or upgrades of existing beam enclosures, building a new target hall versus upgrades of an existing target hall, as well as assessment of any radiation shielding needs.

As discussed before, one of the preferred sites for this facility is the MP9 experimental hall, although other sites are being considered. A preliminary evaluation of these areas regarding potential environmental impact is warranted. The relevant components of such an evaluation include the need for construction, the requirements for a target station (including the protection of soil and ground water activation) and shielding to control general background rates.

The preferred construction site is in a region that contains the existing ME beam line which was associated with a previous fixed-target experiment. The primary beam transport system would be mostly constructed within existing beam line enclosures that are located in an existing berm and have radiation shielding that conforms to the criteria specified in the Fermilab Radiation Guide. Where possible, the new beamline would use components from other beamlines on site that no longer require them. Since these components and existing infrastructure for a generic beamline already exist, it is anticipated that any environmental impact will be consistent with previous use. Cryogenic components in the RF separated beamline constitute the major difference in this beamline from previous beam configurations in this location. It is expected that the environmental constraints from cryogenic operation in other parts of the laboratory will no doubt apply here as well, and those guidelines will be followed for this proposed facility.

For the proposed experiment, consideration of the configuration and location of the target station is constrained by the optimized conditions of the RF separated beam. Constructing a new station would be preferable from the standpoint of controlling and improving the environmental profile of this facility. One former targeting station (although partially disassembled) was located in the Meson Detector building. Thus other existing target stations, within decommissioned areas of the fixed target regions of the laboratory, can provide some components (such as target components, possibly magnets, support stands, and surrounding steel and concrete shielding). Any useful objects stored elsewhere on-site and incorporated into the new target station, where possible, will minimize the creation of new radioactive material.

Concrete and steel shielding would be installed within the enclosure to keep soil and ground water activation, primarily 3H and 22Na, within the limits prescribed by the Fermilab Radiation Guide (i. e. for community drinking water supplies of 20 pCi per ml for 3H and 0.4 pCi per ml for 22Na, and the discharge limits for surface waters of 2000 pCi per ml for 3H and 10 pCi per ml for 22Na), and within the limits prescribed by DOE Orders.

Muon background, hadron shielding, and effects from the beam dump, will be addressed in a shielding document. At this time no extraordinary constraints exist from these elements that would go beyond the usual scope of environmental impact for this area.

10 Cost and Staffing Estimates

We have been asked by the laboratory to submit the cost and schedule section of this proposal, after a review by the Particle Physics Division, in time for review by the PAC at its Aspen meeting in June 2001. This section is that cost estimate. It is the major revision to the June 4, 2001 of the 2nd edition of this proposal. It was added after the initial proposal submission on April 2,2001.

In the absence of detailed engineering designs it is impossible to give baseline precision cost estimates. Despite this, we have made an effort to estimate the capital costs for the detector elements of the CKM experiment based on the recent experience of the KTeV project, the SELEX experiment, and experiment 871 at Brookhaven and others. The costs in the tables below do not include engineering costs, SWF, or contingency. We have adopted a scaling procedure based upon the recent cost estimate for the BTeV proposal to include these overheads. These estimates at this point serve only as a guide for the detector costs of the CKM experiment.

10.1 Project WBS definitions

Project WBS definitions	
WBS Level-1	
1.0	Facility and Beam
2.0	Detector Systems
3.0	Project Management and ES&H
4.0	Offline Analysis

Table 38: Project Level-1 WBS definitions.

WBS definitions	
WBS Item (1.0)	Subsystem
1.1	Civil Construction
1.2	Primary Beam
1.3	Secondary Beam
1.4	SCRF Plant and Equipment
WBS Item (2.0)	Subsystem
2.1	Test Beams
2.2	Vacuum Systems
2.3	BTSM, UMS, and KEAT
2.4	Kaon RICH and Pion RICH
2.5	Beam Interaction Veto System
2.6	Vacuum Veto System
2.7	DMS and Exit Time Plane
2.8	Forward Veto System
2.9	CVP, HVS, and Beam Dump
2.10	Muon Veto System
2.11	Trigger and DAQ
2.12	Front-end electronics and HV

Table 39: WBS definitions.

10.2 Methodology

We have based the methodology of this cost review on the recent BTeV proposal cost estimate. Several of us served on the review of that cost estimate so we are familiar with it's structure. It appears to be the present standard for proposal accounting so we have adopted it wholesale with due acknowledgment to it's creators.

We have also adopted an inclusive strategy for costs associated with the experiment. There are several substantial items which could easily be argued to be someone else's costs. In the end this all comes from the same budget so we have chosen to enumerate it all. If some of these items end up outside to scope, and therefore the management responsibility, of the experiment, so be it. We will call these items out in the "cost drivers" section at the end of this chapter.

We will enumerate the capital (M&S) costs associated with each item to level 3 in a WBS structure. In order to reach a fully loaded cost we will sum these capital costs and apply "BTeV scaling" - that is, we will multiply by factors for labor and contingency equal to the average factor used in the BTeV proposal for experimental equipment; $\times 1.46$ and $\times 1.30$ respectively. For beam line and construction costs we will follow the same procedure with factors determined from recent cost estimates done for us by FESS; $\times 1.40$ and $\times 1.20$ respectively. We have estimated the costs for project management and ES&H as 5% of the fully loaded costs; again in analogy with BTeV.

This procedure is approximate and clearly inadequate for a full cost estimate including a complete WBS breakdown with a schedule and funding profile. This level of detail, which would be appropriate for second stage approval and project baselining, is meaningless without significantly more engineering than has been made available to us thus far. We are seeking first stage (scientific) approval. Once we achieve this milestone we will embark upon an engineering design study leading to a technical design report (TDR) which will contain the kind of detail described above. Given the challenging nature of this experiment, we have strived to be conservative in our estimates. A descoping to make it fit into a premature baseline could be fatal.

We have tried to including in this estimate everything and underestimate nothing. We have assumed that all experimental apparatus is new equipment. We do plan to use, and have costed, existing beam line magnets and associated equipment. Costs to refurbish and reinstall this equipment are included.

There are 2 exceptions to this principal. The R&D costs for the SCRF project (1.4.1) are Beams Division funds to the A0 group which support both the SCRF effort and other projects in A0. Our understanding, from the SCRF review held on May 4,2001, is that this project has received about $500K over the the last 3 years. Following BTeV's example, we have not tried to cost offline computing for the experiment (4.0)

Summary of Methodology

- Assume no existing experiment equipment.
- Some beam line components and main ring sections are reused.
- Do not explicitly cost Fermilab or University labor.
- Assume a labor overhead of 46% on the total material cost. This factor was extracted from the BTeV WBS.
- Assume a contingency of 30% on the total material and labor. This factor is taken from the final contingency associated with the BTeV proposal cost after PPD review.
- Assume EDIA, etc. overhead of 40% plus a 20% contingency on construction. These factors are taken from recent FESS estimates

10.3 Beam Costs

Civil Construction			
WBS Item (1.1)	Costing Source	Existing	Total
1.1.1: New target building	FESS / EBD		$680K
1.1.2: Demolish worm Extensions	"		$100K
1.1.3: New cryogenic & RF buildings	"		$432K
1.1.4: New pad for RF section	"		$50K
1.1.5: Main ring sections (existing)	"	$66K	
1.1.6: Detector tunnel enclosure	"		$500K
1.1.7: New detector building	"		$2700K
1.1.8: Site work and utilities	"		$500K
Subtotal M&S Cost		$66K	$4962K

Table 40: Cost Breakdown for Civil Construction.

Primary Beam			
WBS Item (1.2)	Costing Source	Existing	Total
1.2.1: Meson East tunnel repair	FESS / EBD		$708K
1.2.2: Primary beam line	Murphy-SY120	$826K	$115K
Subtotal M&S Cost		$826K	$823K

Table 41: Cost Breakdown for primary beam.

Secondary Beam			
WBS Item (1.3)	Costing Source	Existing	Total
1.3.1: Target Station	ext beams group	$382K	$756K
1.3.2: Magnets	ext beams group	$2054K	$600K
1.3.3: Collimators/Stopper/neutral dump	ext beams group		$125K
1.3.4: Instrumentation	ext beams group	$13K	$220K
Subtotal M&S Cost		$2449K	$1701K

Table 42: Cost Breakdown for Secondary Beam.

SCRF plant and equipment			
WBS Item (1.4)	Costing Source	Existing	Total
1.4.1: SCRF R&D	SCRF Review		see text
1.4.2: Cavities	"		$2450K
1.4.2.1 Fabrication	"		[$2000K]
1.4.2.2 Preparation and Testing	"		[$450K]
1.4.3: RF power	"		$850K
1.4.4: Controls	"		$100K
1.4.5: Cryogenic plant	"		$880K
Subtotal M&S Cost			$4280K

Table 43: Cost Breakdown for SCRF plant and equipment.

Construction and Beam Systems Cost Roll-up			
WBS Item (1.0)	Subsystem	Existing	New
1.1	Civil Construction	$66K	$4962K
1.2	Primary Beam	$826K	$823K
1.3	Secondary Beam	$2449K	$1701K
1.4	SCRF Plant and Equipment		$4280K
Total M&S costs:		$3341K	$11766K
Total M&S and 40% Labor overhead:			$16472K
Total (M&S+Labor) with 20% contingency:			$19767K

Table 44: Construction and Beam Systems Cost Roll-up.

Test Beams			
WBS Item (2.1)	Costing Source	Amount	Total
2.1.1: CKM Test Stand DAQ	Ramberg		$25K
2.1.2: Veto module XYZ cradle	”		$25K
2.1.3: 1-GeV electron magnets	”		$100K
2.1.4: electron vacuum transport	”		$25K
2.1.5: Additional Cerenkov tagger	”		$25K
Subtotal M&S Cost (Above existing facility equipment.)			$200K

Table 45: Cost Breakdown for Test Beam Components.

Vacuum Systems			
WBS Item (2.2)	Costing Source	Amount	Total
2.2.1: Vacuum vessel.	KTeV		$936K
2.2.2: Vacuum pumps.	Market Survey		$150K
Subtotal M&S Cost			$1086K

Table 46: Cost Breakdown for the Vacuum System Components.

BTSM, UMS, and KEAT Systems.			
WBS Item (2.3)	Costing Source	Amount	Total
2.3.1: Wire Chambers.	HyperCP/Dukes.	9 chambers	$468K
2.3.2: Chamber tables.	HyperCP/Dukes.	3	$60K
2.3.3: Helium bags.	KTeV estimate.	8	$16K
2.3.4: Gas system.	KTeV estimate.		$15K
2.3.5: BM-105 magnets.	Costed in WBS 1.0	—	—
2.3.6: Beam Time Stamp.	Dukes		$60K
2.3.7: Prototype Development.	Dukes		$80K
Subtotal M&S Cost			$699K

Table 47: Cost Breakdown for the Beam Time Stamp Module, Upstream Magnetic Spectrometer, and the KEAT system.

kaon RICH and pion RICH				
WBS Item (2.4)	Costing Source	Amount		Total
2.4.1: Kaon RICH Optics/vessel.	Jim Kilmer			$557K
2.4.2: Kaon RICH gas system.	"			$143K
2.4.3: Kaon RICH PMT(R647) + base.	Hamamatsu	1000 ch.		$271K
2.4.4: Pion RICH Optics/vessel.	Jim Kilmer			$374K
2.4.5: Pion RICH gas system.	"			$100K
2.4.6: Pion RICH PMT + base.	Hamamatsu	3000 ch.		$1350K
2.4.6.1: Hamamatsu R760	"	3000 ch.	$1200K	
2.4.6.2: Hamamatsu R960	"	3000 ch.	$912K	
2.4.6.3: Hamamatsu base.	"	3000 ch.	$150K	
Less labor included in estimate	Jim Kilmer	3 man-years		($251K)
Subtotal M&S Cost (R760)				$2554K
Subtotal M&S Cost (R960)				$2256K

Table 48: Cost Breakdown for the kaon RICH and pion RICH.

Beam Interaction Veto System				
WBS Item (2.5)	Costing Source (VVS scaled)	Amount		Total
2.5.1: Plastic Scintillator.	Bicron BC-404	5.1K tiles		$281K
2.5.1.1: Regrind Injection mold.			$281K	
2.5.1.2: Premix Injection mold.			$102K	
2.5.2: Lead Sheet (1 mm t).	FOB Milwaukee	1.9K quads		$14K
2.5.3: WLS Fiber (1^o ϕ).	Bicron BCF-92	113 km		$79K
2.5.4: PMT assemblies.	Hamamatsu & KTeV	240		$131K
2.5.5: Misc mechanical.	KTeV estimate			$10K
2.5.6: Prototype modules.	VVS Prototype-1			$15K
Subtotal M&S Cost (Bicron-high)				$530K
Subtotal M&S Cost (Bicron-low)				$351K

Table 49: Cost Breakdown for the Beam Interaction Veto System.

Vacuum Veto System				
WBS Item (2.6)	Costing Source (Goloskie)	Amount		Total
2.6.1: Plastic Scintillator.	Bicron BC-404	44K tiles		$882K
2.6.1.1: Regrind Injection mold.			$2425K	
2.6.1.2: Premix Injection mold.			$882K	
2.6.2: Lead Sheet (1 mm t).	FOB Milwaukee	16K quads		$117K
2.6.2.1: Small quadrants.		8.6K	$62K	
2.6.2.2: Large quadrants.		7.1K	$55K	
2.6.3: WLS Fiber (1^o ϕ).	Bicron BCF-92	980 km		$686K
2.6.4: PMT assemblies.	Hamamatsu & KTeV	2200		$1152K
2.6.4.1: PMT.	KTeV estimate	"	$660K	
2.6.4.2: Base.	"	"	$176K	
2.6.4.3: Magnetic shield.	"	"	$55K	
2.6.4.4: Window.	"	"	$66K	
2.6.4.5: Clamping system.	"	"	$44K	
2.6.4.6: O-ring/Spring washer.	"	"	$8K	
2.6.4.7: Flange, welded.	"	"	$132K	
2.6.4.8: Fiber cookies.	"	"	$11K	
2.6.5: Tyvek	KTeV estimate	9200 sq yd		$8K
2.6.6: Steel strong-backs.	KTeV estimate	145		$37K
2.6.7: Vessel/flange bolts.	KTeV estimate	1100		$17K
2.6.8: Assembly fixtures.	KTeV estimate			$5K
2.6.9: Light shield/vac barrier	KTeV estimate			$10K
2.6.10: Prototype modules.	KTeV/Prototype-1			$100K
Subtotal M&S Cost (Bicron-high)				$4558K
Subtotal M&S Cost (Bicron-low)				$3014K

Table 50: Cost Breakdown for the Vacuum Veto System Components.

Downstream Magnetic Spectrometer & ETP			
WBS Item (2.7)	Costing Source	Amount	Total
2.7.1: Prototyping costs.	Nguyen		$50K
2.7.2: Production tooling.	Krider est.		$85K
2.7.3: Chamber Stations.	Krider est.	4 stations	$350K
2.7.4: Production tooling.	Krider est.		$85K
2.7.5: Vacuum Components.	Kenzadori est.		$100K
2.7.6: Gas System.	Nguyen		$50K
2.7.7: Spectrometer magnet coils.	KTeV/Jensen		$750K
2.7.8: Spectrometer magnet iron.	guess		$250K
2.7.9: Exit Time Plane, (ETP).	Scaled to BTSM		$93K
Subtotal M&S Cost			$1813K

Table 51: Cost Breakdown for the DMS/ETP System Components.

Forward Veto System			
WBS Item (2.8)	Costing Source (Goloskie)	Amount	Total
2.8.1: Scintillator pieces.	KTeV cast+50%	$455m^2$	\$202K
2.8.2: Lead pieces.	Vulcan		\$40K
2.8.3: WLS Fibers.	Bicron	36 km	\$25K
2.8.4: PMT assemblies.	KTeV/Goloskie	1800	\$666K
2.8.5: Support Stand.	KTeV/Goloskie		\$20K
2.8.6: Frame/Light shield.	KTeV/Goloskie		\$25K
Subtotal M&S Cost			\$978K

Table 52: Cost Breakdown for the Forward Veto System.

CVP, Hole Veto System, and Beam Dump			
WBS Item (2.9)	Costing Source	Amount	Total
2.9.1: Conversion Veto Plane	Scaled to BTSM		\$93K
2.9.2: HVS beam kicker.	KTeV/H. White	1 BM-109	\$50K
2.9.3: HVS Scintillator pieces.	KTeV cast+50%	$14m^2$	\$6K
2.9.4: HVS Lead pieces.	Vulcan		\$2K
2.9.5: HVS WLS Fibers.	Bicron	1.1 km	\$1K
2.9.6: HVS PMT assemblies.	KTeV/Goloskie	49	\$20K
2.9.7: HVS Support Stand.	KTeV/Goloskie		\$5K
2.9.8: HVS Frame/Light shield.	KTeV/Goloskie		\$5K
2.9.9: Kaon beam dump.	guess		\$25K
Subtotal M&S Cost			\$207K

Table 53: Cost Breakdown for the CVP, HVS, and Beam Dump.

Muon Veto System			
WBS Item (2.10)	Costing Source	Amount	Total
2.10.1: Design/prototypes.	IHEP		\$20K
2.10.2: Scintillator slats.	IHEP	1920	\$192K
2.10.3: PMT assemblies (FEU-115M).	IHEP	3840	\$346K
2.10.4: Support structures.	IHEP		\$50K
2.10.5: Iron absorber slabs.	FNAL steel		\$250K
2.10.6: Misc. shipping charges.	IHEP		\$22K
Subtotal M&S Cost			\$880K

Table 54: Cost Breakdown for the Muon Veto System.

Trigger and DAQ			
WBS Item (2.11)	Costing Source	Amount	Total
2.11.1: Data sum/collectors.	Engineered guess		$474K
2.11.2: Trig sum/collectors.	"		$123K
2.11.3: Level-2 modules.	"		$256K
2.11.4: Level-3 farm PCs.	"		$384K
2.11.5: Output tape drives.	"		$40K
2.11.6: Clock-gen/distribution.	"		$221K
2.11.7: 6U/9U crates and power.	"		$610K
2.11.8: VME system controllers.	"		$180K
2.11.9: Scalers, scopes, analyzer.	"		$55K
Subtotal M&S Cost			$2343K

Table 55: Cost Breakdown for the Trigger and DAQ.

Front-end Electronics and High Voltage				
WBS Item (2.12)	Costing Source	Channels	Cost/chan.	Total
2.12.1: Wire chamber ASD.	HyperCP/CDF	22,000	$10	$220K
2.12.2: QIE-TDC boards.	CDF QIE boards.	6,180	$200	$1236K
2.12.3: TDC boards.	CDF TDC boards.	28,000	$20	$560K
2.12.4: HV-BVS/VVS/FVS/HVS (high).	CAEN	4,300	$200	$860K
2.12.4: HV-BVS/VVS/FVS/HVS (low).	CW base.	4,300	$60	[$258K]
2.12.5: HV-MVS.	CAEN/3 or CW base	3,840	$65	$231K
2.12.6: HV-fiber, BTSM/ETP/CVP.	CAEN/10 + cows.	2,100	$10	$21K
2.12.7: HV-RICH.	CAEN/10 + cows.	4,000	$50	$200K
Subtotal (high) M&S Cost				$3586K

Table 56: Cost Breakdown for the Front-end Electronics and High Voltage.

Detector System Cost Roll-up		
WBS Item (2.0)	Subsystem	System Cost
2.1	Test Beams	$200K
2.2	Vacuum Systems	$1,086K
2.3	BTSM, UMS, and KEAT	$699K
2.4	Kaon RICH and Pion RICH	$2,554K
2.5	Beam Interaction Veto System	$351K
2.6	Vacuum Veto System	$3,014K
2.7	DMS and ETP	$1,813K
2.8	Forward Veto System	$978K
2.9	CVP, HVS, and Beam dump	$207K
2.10	Muon Veto System	$880K
2.11	Trigger and DAQ	$2,343K
2.12	Front-end electronics and HV	$3,586K
Total M&S costs:		$17,711K
Total M&S and 46% Labor overhead:		$25,858K
Total (M&S+Labor) with 30% contingency:		$33,615K

Table 57: Detector System Cost Roll-up.

10.3.1 Construction and Beam Systems Cost Roll-up

10.4 Detector Costs

10.4.1 Detector System Cost Roll-up

All detector costs are summarized in table 57. To reach a full loaded cost estimate we have applied at factor of $\times 1.46$ (+46%) to the total M&S costs to cover labor and then a factor of $\times 1.30$ (30%) for contingency. These cost factors are the averages applied in the BTeV cost estimate ("BTeV scaling").

10.4.2 Comparison with 1st Edition Detector Cost Estimates

The summary and total of all costs enumerated in the 1st edition are in Table 58. We have broken out the electronic and vacuum component of each 1st edition cost estimate, where they were included in each sub-system, and reordered the table to correspond with the present WBS breakdown.

The cost escalation for the detector from the 1st edition (April 1998) to the 2nd edition (now) is nearly a factor of 2. This increase has two major sources. The largest effect is that almost all detectors are now costed relative to actually built complete systems. This list includes as built costs from the following detectors:

Built Complete Systems Used as Cost References

- test beam - none
- Vacuum systems - KTeV vacuum system
- UMS/KEAT - HyperCP MWPC built by the UVA group

- BTMS/ETP/CVP - none
- DMS - BNL E871 straw chambers built by the Texas group
- DMS magnet - KTeV magnet built by the Fermilab group
- K RICH - Selex RICH built by the Fermilab group
- VVS/BIVS - KTeV ring vetos built by the Fermilab group
- Pi RICH - Selex RICH built by the Fermilab group
- FVS - some information from KTeV CsI and vacuum veto system
- MVS - MVS prototype built by the IHEP group
- High Voltage - vendor prices
- MVS - MVS prototype built by the IHEP group
- electronics - CDF ADC system built by Fermilab and CDF TDC systems built by the Michigan group
- Trigger & DAQ - none

The second cost escalator is that we have significantly increased channel counts in several systems. These include:

- UMS - silicon strips $\rightarrow$ MWPC's with a TDC on each wire
- VVS/BIVS - doubled the number of PMTs with an HV, ADC and TDC on each
- MVS - doubled the number of PMTs (each scintillator end) with an HV, on each PMT and an ADC and TDC on each scintillator

A fully instrumented PMT channel with the tube, base, HV, ADC and TDC costs about \$950. We've added a total of 2200 PMTs, most fully instrumented.

These additions were motivated by design and physics considerations. They must be qualified by test beam results. It is possible that we have over done it and that some of these additions could be reduced.

10.5 System Cost Roll-up

The total systems costs are summarized in table 59. As a reality check we can compare to the KTeV experiment which has many similarities with CKM. Both are high rate, high precision, kaon decay in flight experiments. Both have (or had) to build a new detector hall, an all new detector and make major modifications to an existing beam line. KTeV was built with a total capital cost for the detector, detector hall and beam line of about \$24M. The peak year of the KTeV spending profile was 1995. Correcting this cost for 6 years of inflation at $3\%/year$ yields a cost of $\$24M * (1.03)^6 = \$28.7M$ in FY2001 dollars. This is unreasonably close to our present capital cost estimate of \$29.5M.

Comparison of Detector Cost Estimates				
	2nd edition		1st edition	
WBS	Detector System	Cost	System	Cost
2.1	Test Beams	$200K		
2.2	Vacuum Systems	$1086K	Vacuum Veto	$1000K
			BTSM System	$305K
			UMS System	$90K
			KEAT System	$40K
2.3	BTSM, UMS, and KEAT	$699K	sub-total	$435K
			Kaon RICH	$318K
			Pion RICH	$1300K
2.4	Kaon RICH &Pion RICH	$2554K	sub-total	$1618K
2.5	Beam Interaction Veto	$351K	BIV System	$213K
2.6	VVS System	$3014K	Vacuum Veto	$1540K
2.7	DMS and ETP	$1813K	DMS/ETP System	$1300K
2.8	Forward Veto System	$978K	FVS System	$825K
			CVP System	$285K
			HVS System	$63K
2.9	CVP, HVS, &Beam Dump	$207K	sub-total	$348K
2.10	Muon Veto System	$880K	MVS System	$400K
			Trigger System	$300K
			DAQ System	$700K
2.11	Trigger and DAQ	$2343K	sub-total	$1000K
			UMS System	$80K
			KEAT System	$40K
	22,000 ASD + TDC	$660K	sub-total	$120K
			Kaon RICH	$41K
			Pion RICH	$225K
	4,000 HV + TDC	$280K	sub-total	$266K
			BIV System	$15K
			Vacuum Veto	$180K
			FVS System	$155K
			HVS System	$7K
	4300 HV + TDC-ADC	$1720K	sub-total	$357K
			BTSM System	$30K
			DMS/ETP System	$800K
			CVP System	$30K
		$292K	sub-total	$860K
	3840 +HV/3+TDC-ADC/2	$634K	MVS System	$75K
2.12	Electronics and HV	$3586K	total	$1678K
Total		$17711K		$10357K

Table 58: Comparison of April 1998 (1st edition) and present detector cost estimates

System Cost Roll-up				
WBS Item	System	M&S costs	plus Labor	plus contingency
1.0	Facility and Beam	\$11,766K	\$16,472K	\$19,767K
2.0	Detector Systems	\$17,711K	\$25,858K	\$33,615K
3.0	Project Management - ES&H			\$2,669K
4.0	Offline Analysis			
Total		\$29,477K	\$42,330K	\$56,051K

Table 59: System Cost Roll-up.

10.6 Critical & Notable Cost Drivers

Critical cost drivers and some other notable costs are summarized in table 60.

In the Facility and Beam section we have included a new detector building at the explicit request of the Fermilab director. We have also included reconstruction and repair funds for the primary Meson East beam line and tunnels. These repairs are required to prevent things like the structural failure of some of the beam line tunnels. The cost estimate for the SCRF is based upon estimates made while the technical development of the cavity technology is still on-going. There is significant uncertainty in the SCRF cost estimate.

In the detector cost estimate we have made several preliminary choices in a somewhat arbitrary manner. We chose to cost the less expensive scintillator solution offered by Bicron. We haven't tested this scintillator yet, although the manufacturer claims it has the same properties as the more expensive scintillator from Bicron, which our tests show to exceed our requirement. There are also several other scintillator vendors in the former Soviet Union which may be able to provide an even less expensive solution with acceptable performance. We have just begun to evaluate these products for acceptability. Our preference will be for more than one scintillator vendor to avoid being held hostage to production delays and quality problems.

We opted to cost the more expensive 1/2 inch PMT's for the pion RICH. We just learned that a new, cheaper, tube is available. We have not yet completed the studies to evaluate cost-benefit for this choice. Likewise we have chosen to cost a relatively expensive Hamamatsu PMT for the VVS without a full market survey.

The spectrometer magnet cost is scaled to replicate the KTeV magnet. We, in principal, don't need a magnet this long but we have not yet done any engineering to understand what cost savings, if any, can be realized.

We are costing the ADC-TDC readouts at \$200/channel based upon the as-built costs from CDF. The CDF design has considerably more functionality than we require. We suspect that a significant cost saving is possible in the system. We are also costing the individual PMT high voltage channels at the full price for new, commercially produced, programmable high voltage systems.

10.7 Staffing

Our list of proponents is dominated by physicists with significant experience in doing rare and ultra-rare kaon decay experiments of this kind. The present collaboration has grown by a factor of two since the submission of our 1st edition of this proposal in April 1998. We have been joined by a group from the Brookhaven National Laboratory who are senior members of BNL787/949, and by two major University groups, Michigan and Virginia. The Fermilab group has doubled in size

Critical & Notable Cost Drivers			
WBS Item	System	System Cost	Issue
1.1.7	New detector building	$2,700K	Directorial mandate
1.2.1	Meson East tunnel repair	$708K	Reconstruction and repair
1.4	SCRF plant and equipment	$4,280K	R&D still in progress
Total M&S	Beam critical drivers	$7,688K	65% of total beam costs
2.4.6	Pion RICH PMT(R760) + base	$1,350K	$300K saving if R960 is OK
2.6.1	VVS scintillator	$882K	Low end estimate.
2.6.4	VVS PMTs.	$1,152K	Channel count, Hamamatsu PMT
2.7.7:8	Spect. Magnet.	$1,000K	Large Aperture, high quality.
2.12.2	ADC-TDC boards	$1,236K	$200/channel, 6.2K channels.
2.12.4	Veto HV	$860K	$200/channel, 4.3K channels.
Total M&S	detector critical drivers	$6,460K	37% of total detector costs
Total M&S	critical drivers	$14,148K	48% of total M&S costs

Table 60: M&S costs - Critical & notable cost drivers.

with the addition of two Wilson Fellows, a research associate and several others.

When the university and laboratory groups represented fill out with younger physicists and students we will have a significant fraction of the physics staff required to carry out this experiment. We could profitably add a few more groups to the collaboration. Two more groups, The University of South Alabama and the Institute for Nuclear Research (INR) Troitsk, have recently joined the collaboration.

There seems to be no lack of interest in CKM. University groups have difficulty in joining an effort, such as ours, before it gains official recognition. First stage approval of this proposal is all we believe we require in order to strengthen our collaboration up to a level sufficient to produce a complete and credible design and cost for the experiment. The staffing of the experiment at the engineering and technical levels will require negotiation with the laboratory.