Proposed New Beam Instrumentation II

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I. Introduction

This technote should be read in conjunction with technote K-004. It summarizes the results of beam tests of prototypes of the proposed upgrades to the beam instrumentation, Monte Carlo simulations of various aspects of the upgrade, and describes the evolution of our thinking since K-004 was completed.
We wish to modify the beam instrumentation in order to achieve the following goals:

- Improved spatial resolution at B4 where the incoming particle enters the target. This will be achieved by doubling the number of hodoscope elements, changing their shape, and reading them out with WLS fibers. Two possible shapes for the hodoscope elements were considered:
  a) triangular cross section (Figure 1) and
  b) rectangular cross section (Figure 2).
  Both were tested in the TRIUMF beam and the results of those tests will be described below.

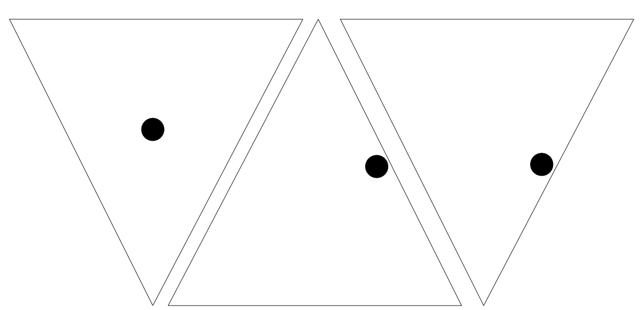

Figure 1: Hodoscope elements used in test

- Improved photon vetoing efficiency for photons coming back along the beamline. In E787, these photons were vetoed by a lead-glass Cerenkov counter (Pb-G) just upstream of B4.In E787 photon vetoing inefficiencies prevented us from looking below

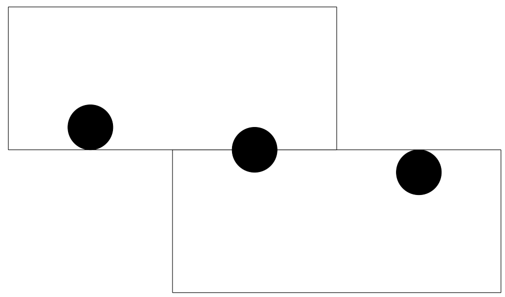

Figure 2: Rectangular B4 hodoscope element

the Kπ2 peak, and the escape of photons along the beamline was a major contributor to the overall inefficiency. We have examined two schemes to improve this situation:

- a) Keep the existing lead-glass counter and add a new segmented photon veto, (BSPV), in the beam just upstream and a Ring Photon Veto (RPV) for photons which escape in the deadspace between the beam photon vetos and the endcaps. (Figure 3),
- b) Remove the lead-glass counter entirely and replace it by a larger BSPV to fill up the space previously occupied by the lead-glass high-field tubes and their lightguides, so that no RPV is required (Figure 4)

For both a) and b) we would add an upstream photon veto(UPV), located where the beam is narrow vertically (this detector does not intercept the beam - see Figure 12)

II. B4 Hodoscope

A. Results of Beam tests of triangular cross-section hodoscope elements

Three hodoscope elements were constructed from BC408 scintillator with triangular cross section (height of equilateral triangle = 12.5mm), and length 8 cm. They were read out by WLS fiber, with both ends of the fiber taken to the phototube (Hamamatsu R580-17 extended green obtained from Princeton). In one of the pieces the WLS fiber passed through the centre of the fiber while in the other two it lay in a groove cut in one side of the scintillator (Figure 1). Optical grease was used to provide good coupling. Each element was individually wrapped and optically isolated from the other two. The test was carried out with a mixed beam of electrons, muons and pions in the M11 beamline at TRIUMF. Measurements were carried out at beam momenta of 100 MeV/c, 200 MeV/c and 300 MeV/c. Trigger counters provided

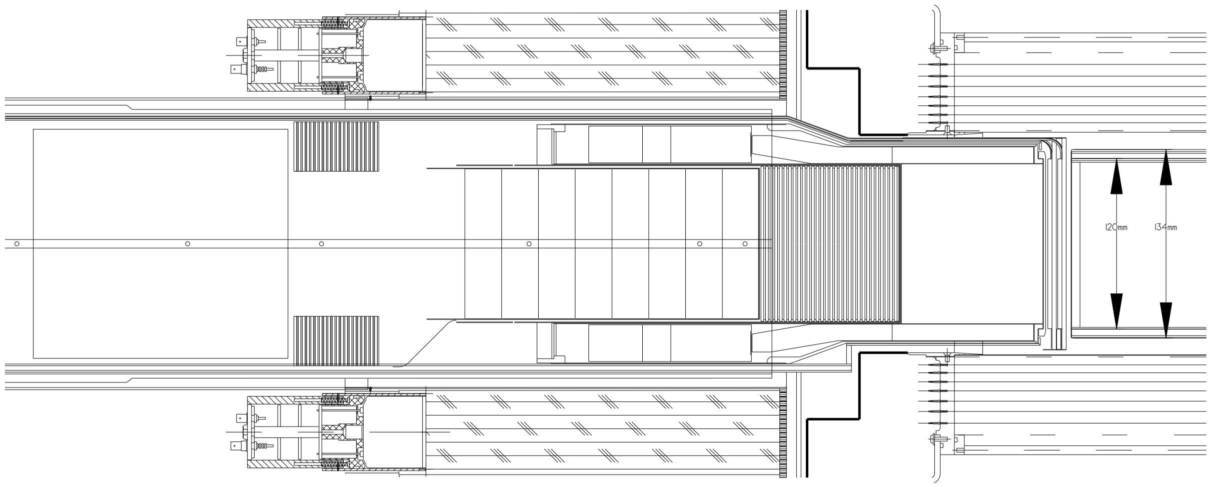

Figure 3: Lead-Glass photon detector with additional Beam Segmented Photon Veto and Ring Photon Veto

timing and pulse height information which aided particle identification. The results of these tests is summarised below:

- The location of the WLS fiber made no discernible difference to the total light output of the hodoscope element.
- Minimum Ionizing Particles (MIP) gave 30 pe in 12.5 mm of scintillator or 25 pe/cm. This is the same as the old B4 with lucite lightguides.
- The timing resolution was about the same (σ=1.1ns) as we obtained with the old B4, and is consistent with that found by other observers.
- Most of the time, a particle passes through adjacent elements, sharing its energy loss between them. The difference in energy loss provides positional information about the location of the particle. The test showed that this difference gave adequate spatial resolution (2-3 mm) for our purposes (Figure 5).
- The sum of the energies deposited by a particle in adjacent elements should be a measure of its energy loss in 12.5 mm of scintillator. Based on the total number of photoelectrons (30), we expect to get a resolution of about σ=25% for this quantity. In the test, we measured a resolution of about 34%The reason for this discrepancy is not known, but one possibility is imperfect gain matching between the hodoscope elements.

An accurate measurement of the dE/dx energy loss of the particle in B4 is crucial to our ability to reject major sources of background, such as π-scats and charge exchange. Because

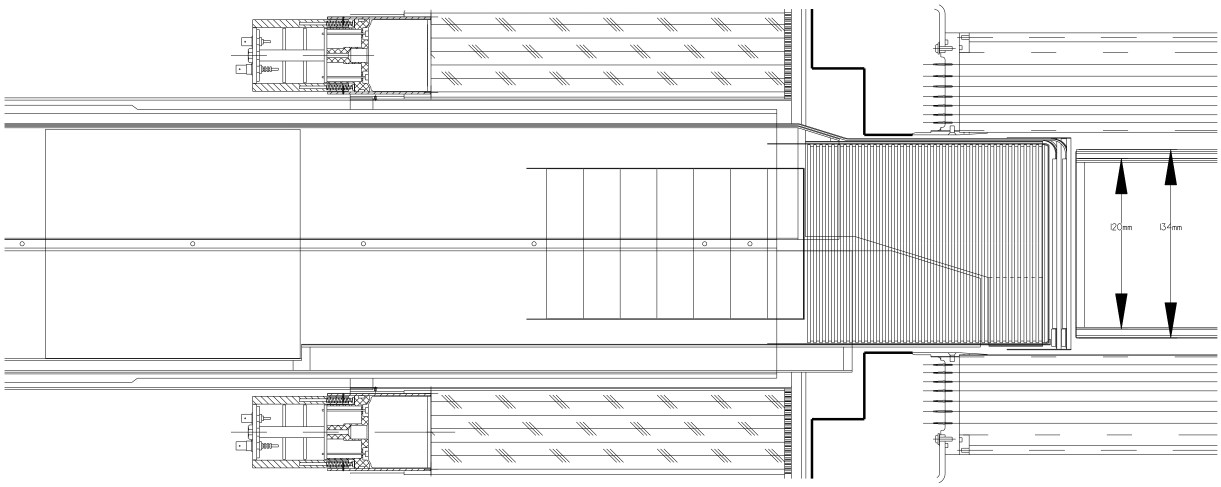

Figure 4: Larger BSPV with Pb-Glass removed and no RPV

of the unexpectedly poor resolution in dE/dx measured with the triangular cross-section elements, we decided to revise the design so that each element was made of a pair of staggered rectangles (see Figure 2) glued together and read out by 3 WLS fibers. (The scintillator is Bicron-BC404, the WLS fiber is Bicron BCF92A double-clad, and the phototube is the Hamamatsu H3165-10.) This design has the advantage that particles go through the same thickness (modulo a factor 2) of scintillator wherever they strike the element. This feature should make gain matching between individual elements easier and improve the dE/dx energy loss resolution. The spatial resolution is now equal to half the width of one of the rectangles, or 3.65 mm, for the sizes shown. The thickness of one layer of B4 is 6.35 mm (Figure 6), so that the total thickness of B4 traversed by a particle is 12.7 mm, the same as before.The WLS readout allows the B4 elements to be made longer, while still fitting within the UTC. As may be seen in Figure 7, the hodoscope elements now extend to cover the I and V counters (which are also covered by the 2-segment ring veto counter shown in Figure 7), so that the location of particles which stop or scatter in the I-counters may be determined.Figure 8 shows a 3-D view of one hodoscope. This arrangement allows the lead-glass Cerenkov counter to be moved as close to the target as it was before.

B. Results of Beam tests of rectangular cross-section hodoscope elements

A prototype consisting of 5 rectangular hodoscape elements was built and coupled to H3165 tubes supplied by our Japanese collaborators. The prototype was tested in the M11 beamline at TRIUMF in April,2000. Measurements were made with pions and muons at 200 MeV/c and 100 MeV/c. Trigger counters were used to separate beam pions from muons and to reject electrons. Peaks corresponding to energy loss in a single hodoscope element, and

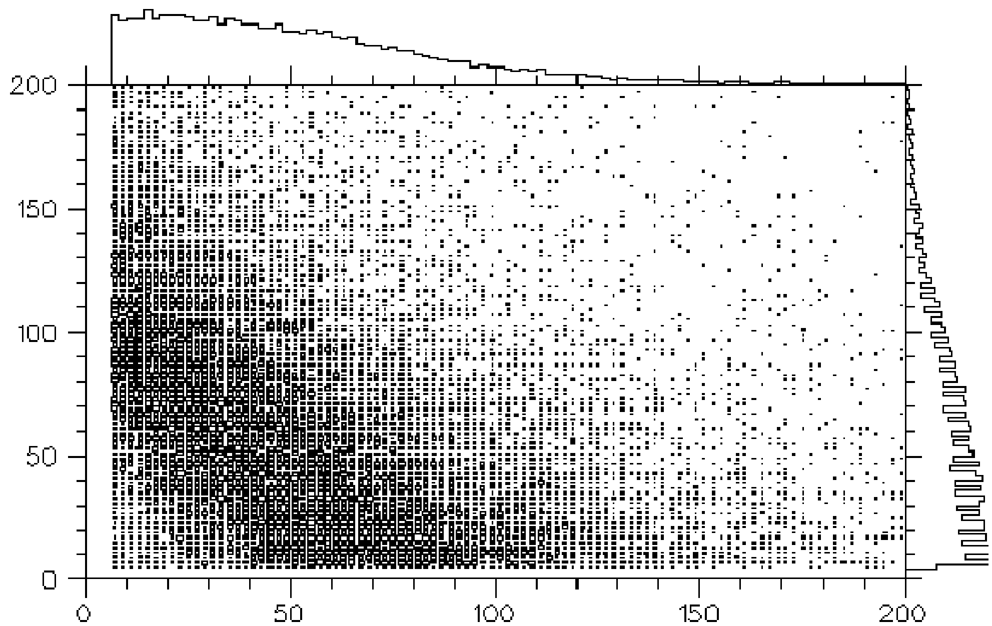

Figure 5: Pulse height(PH) in one element vs PH in adjacent element

energy loss shared more or less equally between two overlapping elements were seen (Figure 9). Single p.e. peaks were identified and used to calculate the response for the three central elements of the 5-element array (Table 1).

Table 1: Rectangular Cross-sectional B4 prototype test

Element	Particle	Energy loss	No. p.e.	No. p.e. per MeV
No.2	muon	1.44 MeV	16p.e.	11
No.3	muon	1.44 MeV	15p.e.	11
No.4	muon	1.44 MeV	16p.e.	10
No.2	pion	1.61 MeV	17p.e.	11
No.3	pion	1.61 MeV	17p.e.	11
No.4	pion	1.61 MeV	18p.e.	11

These results indicate that the number of p.e. per MeV is almost the same as we had with the old B4 (with solid lucite lightguides), and we can expect about 50 p.e. for kaons traversing B4. The resolution in dE/dx should thus be the same as before, and the rectangular cross, giving clean peaks, will allow us to gain-match individual elements without difficulty. A Monte Carlo simulation of the response of B4 to beam kaons and pions, based on a 4000 ray sample with beam momentum 710 MeV/c and initial coordinates derived from measured

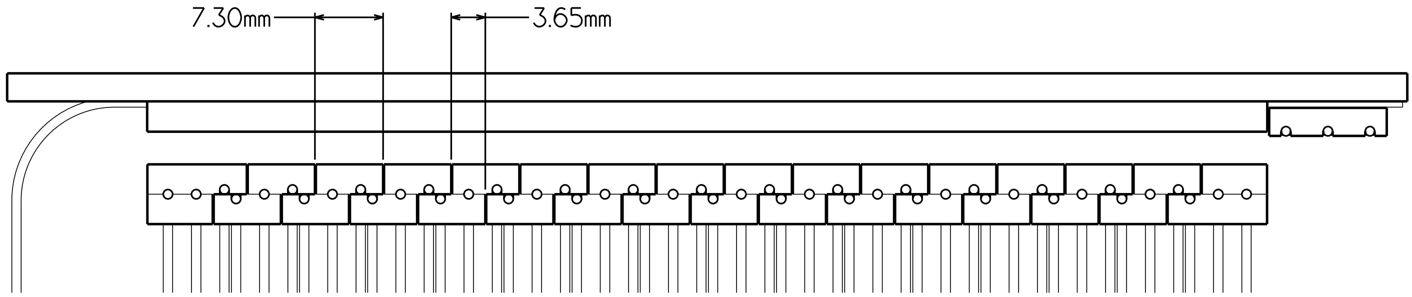

Figure 6: Rectangular B4 hodoscope -top view

values, is shown in Figure 10. We thus expect that K/pi separation from B4 should be similar to what was achieved with the old B4 hodoscope.

III. Photon Veto along beamline

A. Lead-glass photon veto (Pb-G)

The existing active degrader is a lead-glass cylinder with diameter 107.5 mm and length of 101.6 mm (4.5 Radiation Lengths). As noted in the Introduction, we could decide to retain a lead-glass counter, and add an additional photon detector to it, or replace it completely with a new one. Since the replacement of the B4 solid lightguides by WLS readout allows the diameter to be increase by at least 5mm, and since the existing glass appears to have suffered radiation damage, we propose to buy a new piece 5mm larger in diameter and the same length if it is decided to continue using lead-glass.This should increase the probability of detecting photons in this detector by about 10% . We can also take the opportunity to simplify the lightguides.

B. Beam Segmented Photon Veto (BSPV)

We examined a new design of beam photon detector consisting of alternate layers of radiator (1-mm lead or 2-mm copper, for example) and 2-mm thick plastic scintillator discs. In the case where the radiators are 1-mm lead, this corresponds to the total thickness of about 7 radiation lengths. Each scintillator disc is divided into angular sectors,whose scintillation light is converted and transmitted by 15 1-mm diameter, 2-m long double-clad WLS fibers attached at the circumference-arc of each sector (see Figure 11). All scintillator layers in the same sector would be coupled together and read out with the same WLS fibers going to the same phototube. It is important to reduce the chance of getting a kaon and a photon shower in the same sector since the presence of an early kaon hit may block detection of the

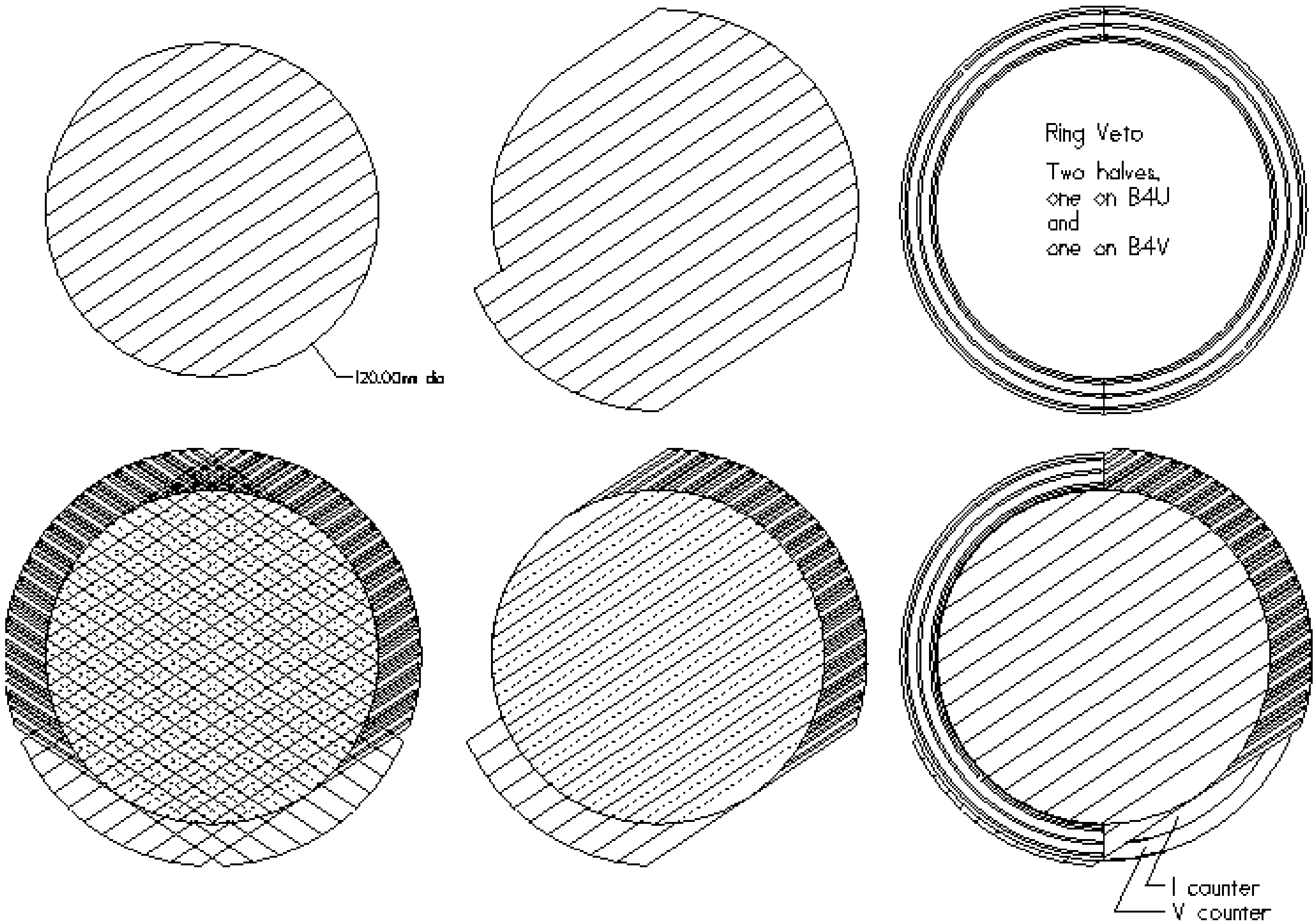

Figure 7: B4 design with rectangular elements, showing B4 hodoscopes and ring veto counters

subsequent photon, especially when the kaon pulse is significantly larger than the photon pulse. The number of sectors is a compromise between loss of photon detection efficiency at low energy, (which goes down as the number of sectors is increased, until the sectors become so small that incident kaons hit more than one sector in traversing the detector), and difficulty of construction.

A prototype sector was constructed and tested in the M11 beamline in May, 2000. The tests indicated that we can expect to get about 10 p.e. per MeV of energy deposited in the scintillator. The major remaining uncertainties are photon detection efficiency (taking the loss of efficiency from the passage of beam kaons into account), and the magnitude of the loss of stopping kaons which will result from scattering and nuclear interactions in this detector. These effects were modelled in Monte Carlo simulations to be discussed later.

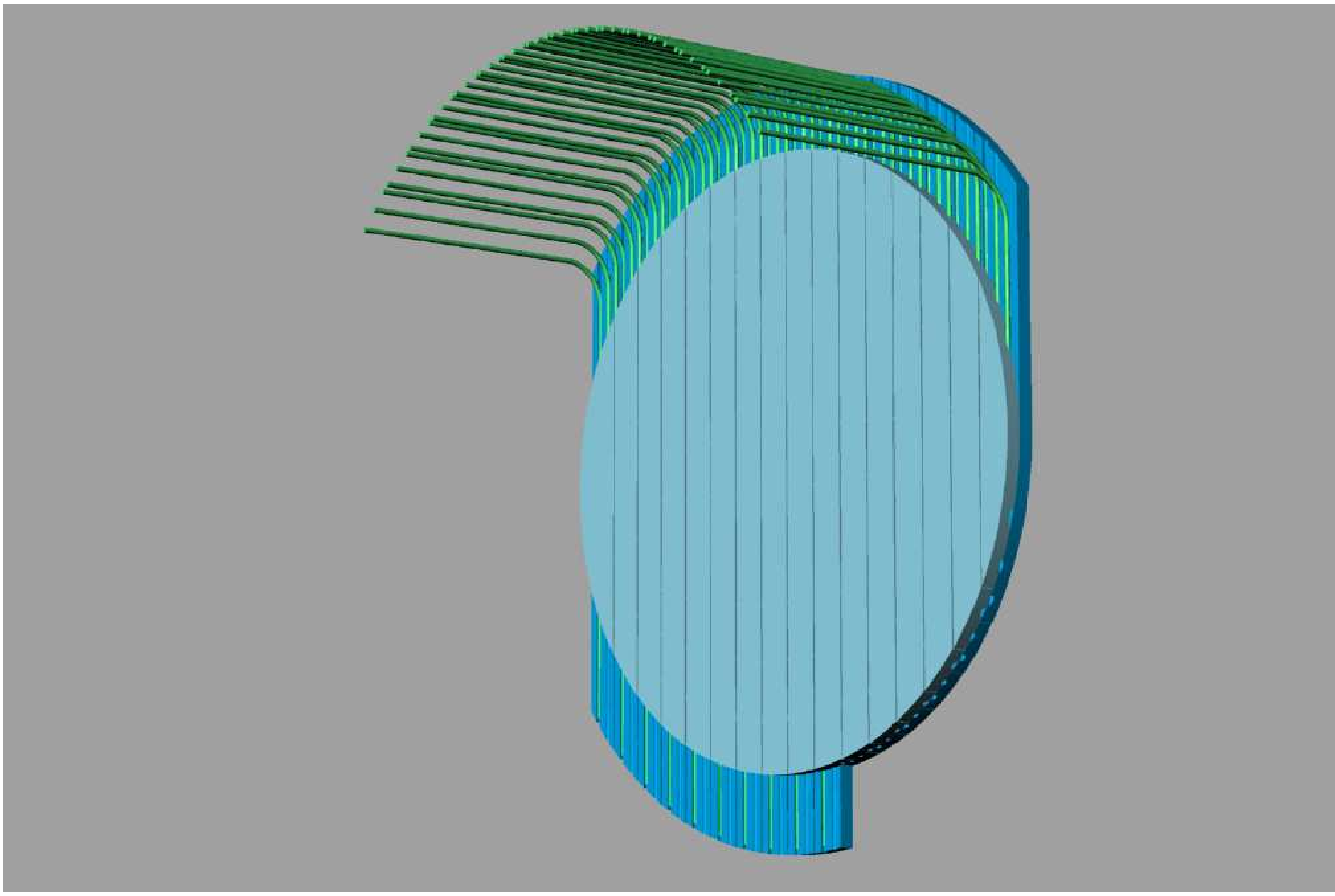

Figure 8: 3-D view of one B4 hodoscope

C. Ring photon Veto

The ring photon veto counter is a cylinder with inner diameter of 102 mm and outer diameter of 170 mm to provide coverage at the perimeter of the active degrader. The construction would be 20 layers of 1mm-lead interspersed with 2 mm scintillator, in 4 segments separately read out by WLS fibers running in grooves along the perimeter of the scintillator. This detector is intended to cover the area between the lead-glass and CsI endcap detectors.

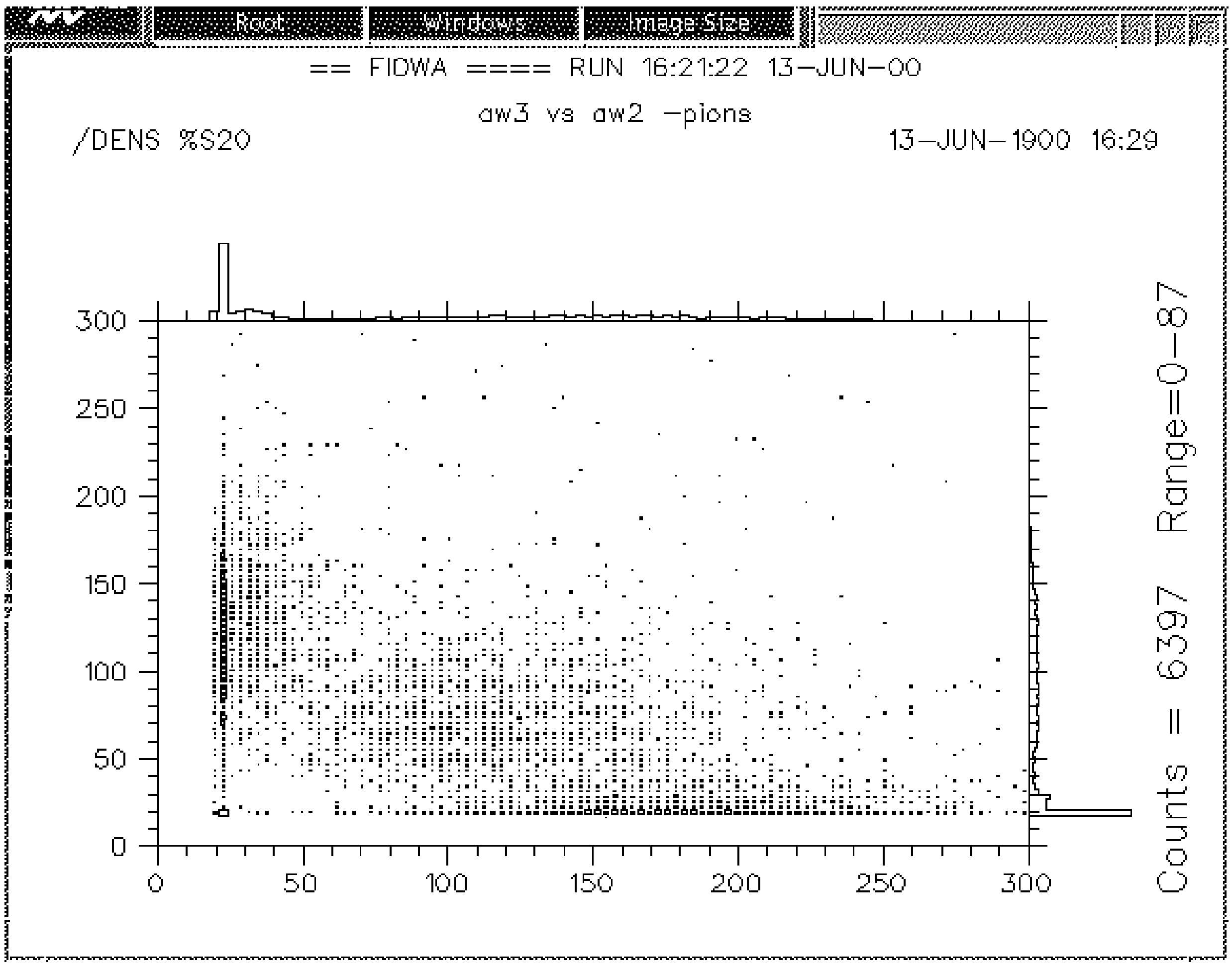

Figure 9: Pulse height in element 3 vs pulse height in element 2 for 200 MeV/c pions

D. Upstream Photon Veto (UPV)

At the present time, there is a hole counter between the Princeton Cerenkov counter and BWC1. The old hole counter has been heavily used in double-beam background study and rejection. However, because of its shape (L) it may not have a good efficiency in some regions, and since the pion beam location is different from kaon's it is desirable to have the hole counter aperture somewhat larger to accommodate it. So, the existing hole counter requires some improvement.

The photon vetoing capability in the upstream direction can be further strengthened by converting the hole counter into a combined hole/photon veto counter, to be installed just downstream of the Princeton Cerenkov. A conceptual design for this new detector consists

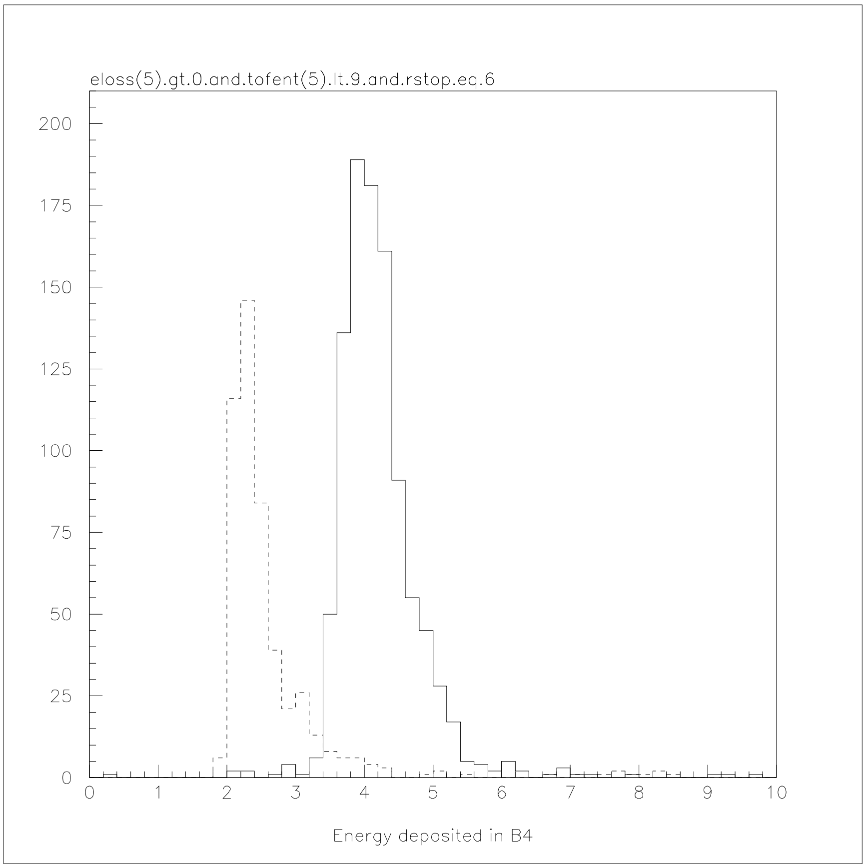

Figure 10: Predicted energy loss in B4 for kaons (solid line) and pions (dashed line) in 710 MeV/c beam. The relative normalization is arbitrary

of a lead/scintillator sandwich with 1mm-thick layers of lead interspersed with 2mm -thick layers of scintillator. With 20 such layers, we would have a total thickness of 60mm and 3.6 Radiation lengths. The diameter should be about 250 mm, so that the 200 mm diameter hole in the endplug is covered. In order to allow the beam to pass through, the detector is split in the horizontal plane and the two halves separated vertically by about 45 mm (Figure 12). At the downstream end of the Princeton Cerenkov counter, where the UPV is located, the beam is wide horizontally and small vertically. The scintillators are read out by WLS fibers running in grooves cut into the scintillator pieces at their outer radii. All the fibers in the upper half go to one tube, with the lower half similarly read out. Such a counter would detect photons passing between the active degrader and the collar. Because of the vertical separation for the beam, coverage would not be complete, but with a vertical separation of 45 mm, coverage would be more than 80 %The vertical separation between the two halves should be made adjustable.

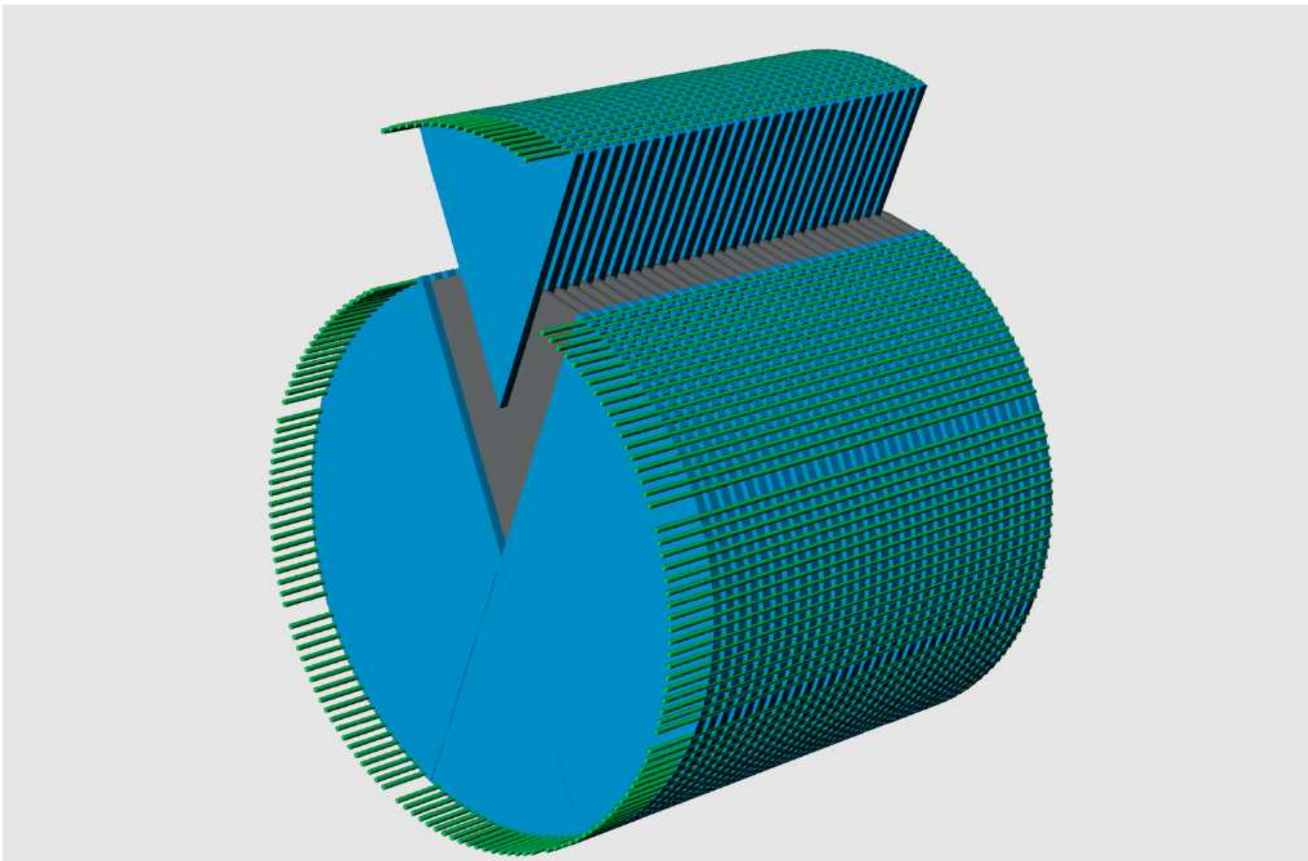

Figure 11: Beam Segmented Photon Veto (BSPV)

IV. Monte Carlo calculations

A. Estimate of reduction in stopped K-rate

Monte Carlo calculations were carried out using a Geant-base simulation of the beam-related parts of the detector between the final quadrupole and the stopping target. This program was originally written by John Haggerty and modified by Vivek Jain.To simulate the beam entering the detector, 4000 rays whose initial coordinates are derived from measured values are used. Each ray is then followed through the various beamline components until it either stops or scatters out of the target.The program can use either of two hadronic packages, called Gheisha and Fluka, to simulate hadronic interactions. Results of calculations made with this program for incident K^+ with momentum 710 MeV/c are summarized in Tables 2 and 3. These calculations were done with the 101.6 mm long lead-glass degrader present. In each case, the length of BeO degrader was adjusted so that the stopping K z-distribution

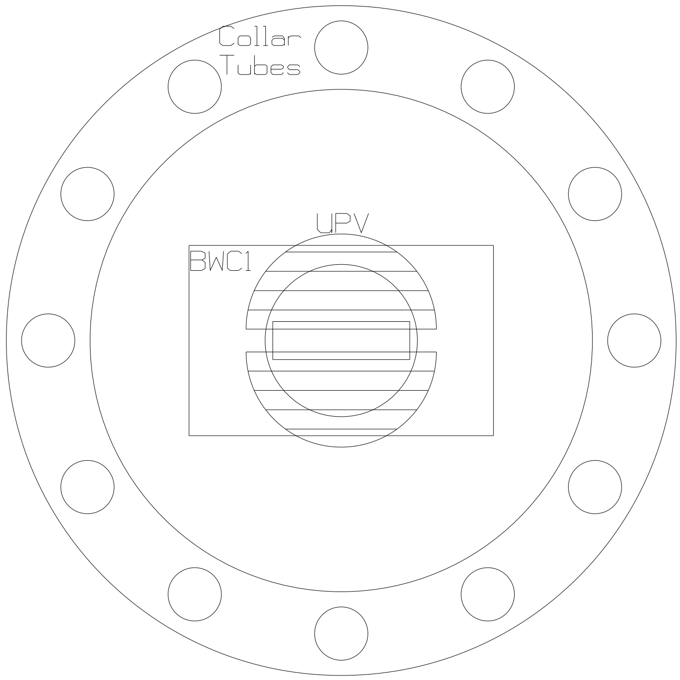

Figure 12: Upstream Photon Veto (UPV)- beams-eye view

was centred at the middle of the target. The detector is made up of multiple layers, each layer consisting of a radiator plus 2mm of plastic scintillator. The number of K-stops as a function of different numbers of layers (for lead radiator) and for differing radiator materials is shown. The statistical accuracy is about 3%Ȧlthough there are substantial differences between the calculations made with the Gheisha and Fluka hadronic packages, trends are similar if we normalize all the Gheisha results to the number of K-stops predicted by Gheisha for no segmented photon veto, and do likewise for all Fluka results. For different radiator materials, the thickness of radiator material was chosen so that it was the same number of radiation lengths as the reference case (1mm lead radiator). Thus all radiator materials considered would result in similar photon detection efficiencies. The calculations shown in Table 3 suggest that the loss of K-stops is minimized by choosing a radiator material in the copper-iron region of the periodic table, rather than using a heavy metal. This rather unexpected conclusion may be explained by noting that the amount of additional BeO degrader needed to stop the beam in the centre of the target is substantially greater if higher-Z radiators are utilized. Thus the total material in the path of the beam, measured in either radiation or interaction lengths, is greater the higher the Z of the radiators.

Table 2: MC calculations of Kstop - Pb radiator

Seg. Live degrader		Rad Len		Rel.Kstops- % change	
Radiator	Layers	P-Veto	Total	gheisha pkg.	fluka pkg.
none	none	3.8	5.7	0	0
1mm Pb	5	4.7	6.2	-4.2	-3.5
1mm Pb	10	5.6	7.1	-6.7	-6.6
1mm Pb	15	6.5	8.0	-7.5	-9.0
1mm Pb	20	7.3	8.9	-11	-10

Table 3: MC calculations of Kstop - Radiator dependence

Seg. Live degrader		Rad Len		Rel.Kstops- % change	
Radiator	Layers	P-Veto	Total	gheisha pkg.	fluka pkg.
none	none	3.8	5.7	0	0
1mm Pb	20	7.3	8.9	-11	-10
.571mm U	20	7.3	8.9	-12	-13
.625mm W	20	7.3	8.8	-10	-10
2.16mm Sn	20	7.3	8.7	-7.2	-9.7
2.55mm Cu	20	7.3	8.3	-2.7	-6.6
3.14mm Fe	20	7.3	8.2	-1.4	-3.1
4.62mm V	20	7.3	8.0	-5.1	-6.8
6.36mm Ti	20	7.3	8.0	-5.4	-6.9

B. Copper radiators - stopped K-rate

These considerations induced us to examine the copper radiator configuration in more detail (iron is obviously not an option inside the solenoid). Calculations for a 2mm-Cu radiator are shown in Table 4 . The first four rows are for configurations with the lead-glass active degrader present, while the last two rows are for 40 layers of 2mm-Cu+2mm-scintillator with the lead-glass active degrader removed. These results suggest that the number of stopped kaons will increase by several percent for this last configuration, which has the additional advantage that the removal of the lead-glass and its associated lightguides and high-field phototubes greatly simplifies the mechanical construction and allows the diameter of the BSPV to be increased to 137.5 mm.

C. Copper radiators-vetoing inefficiency

We used the same Monte Carlo program to investigate the loss of photon vetoing efficiency when a photon hits a sector of the photon veto through which the incident kaon has passed.The assumption is made that if the energy deposited by the kaon in the sector is

Table 4: MC calculations of Kstop - Cu radiator

Seg. Live degrader		Rad Len		Rel.Kstops- % change	
Radiator	Layers	P-Veto	Total	gheisha pkg.	fluka pkg.
none	none	3.8	5.7	0	0
2mm Cu	10	5.2	6.7	-2.6	-1.6
2mm Cu	20	6.6	7.7	-3.5	-6.3
2mm Cu	40	5.6	6.7	+9.0	+5.7

greater than some threshold (THRESH), then that sector is dead to photons for that event. The resulting inefficiency, as a function of the number of sectors and the threshold energy, is shown in Table 5. The second row of the this Table gives the inefficiency which would result if the kaon path were confined to a single sector. Subsequent rows show what happens when the kaon follows the Monte Carlo simulated path. These results suggest that there is little to be gained by increasing the number of sectors beyond 12.

D. Monte Carlo calculations with copper radiators-response

The response of the segmented photon veto to 710 MeV/c kaons and pions (with the usual initial beam coordinates) is shown in Figure 13. A clear separation between kaons and pions exists, allowing this detector to aid in the rejection of background.

Table 5: MC calculations - vetoing inefficiency from kaon pulse

Number of sectors	24	12	8	6	4
single sector ineff.	0.042	0.083	0.125	0.167	0.25
Threshold (MeV)					
0.3	0.115	0.134	0.161	0.193	0.264
0.5	0.114	0.133	0.160	0.192	0.263
1.0	0.107	0.125	0.154	0.186	0.259
2.0	0.096	0.114	0.145	0.176	0.252
3.0	0.087	0.107	0.136	0.170	0.250

E. Monte Carlo calculations of photon detection efficiency

Calculations of photon detection efficiency were carried out in the same way as described in Technote K-008, with the following changes and improvements:

- For the existing geometry , "Lead glass" is now really lead glass instead of lead/scintillator sandwiches, and a Poisson distribution with an average photo-tube hit of 0.1 pmt/MeV?

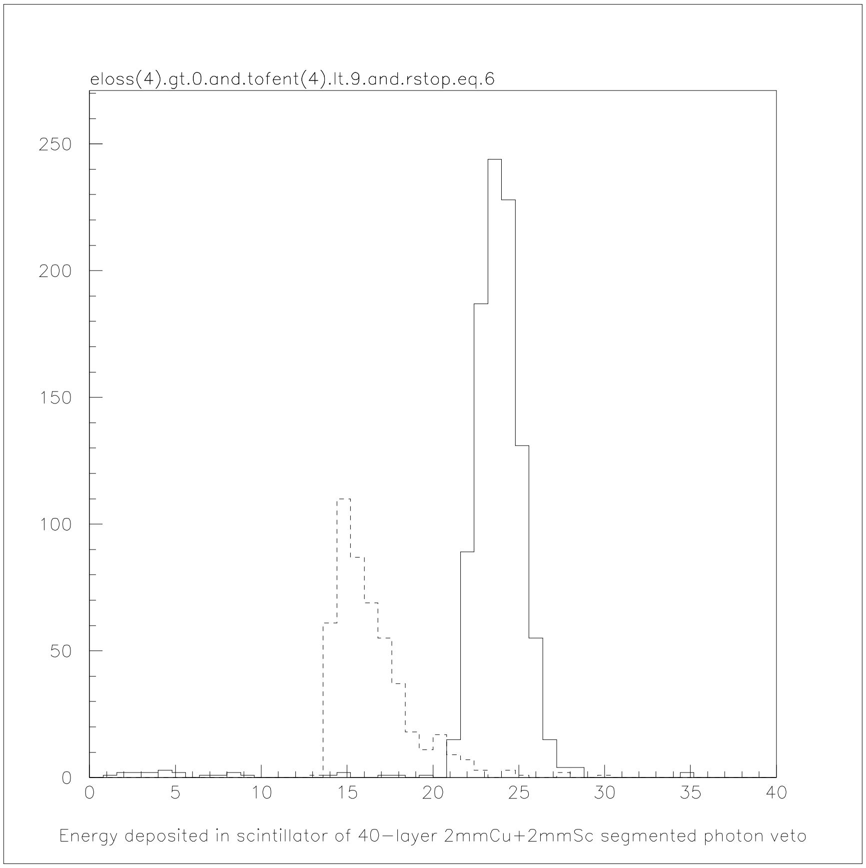

Figure 13: Predicted energy loss in segmented photon veto for kaons (solid line) and pions (dashed line) in 710 MeV/c beam. The relative normalizations are arbitrary

is used in the analysis. More than one hit is required to veto the event—this is the requirement used in the $\pi\nu\bar{\nu}1$ analysis.

- For the new geometry, sandwiches of Cu (2 mm) and plastic scintillator (2mm) are used to allow more kaon stops in the target. The blinding effect caused by the incoming kaon discussed earlier is included in these results; the distribution of numbers of dead sectors is taken from the beam MC calculations , and inefficiencies were added with the weights by the beam MC calculations.

- Changes in the other conditions include: The outer diameter of the existing lead glass is 107 mm and that of the new BSPV with no lead glass is 137.5 mm.

The results of these calculations are shown in Figure 14.

In the existing geometry the photon detection inefficiency for 20 MeV photons, increased about a factor of four compared to the previous analysis (see Technote K-008), due to two improvements newly introduced in the analysis.These improvements are the use of the Poisson distribution and the requirement that the number of phototubes firing be greater than 1. The effects of these changes are almost invisible for higher energy photons. The closed circles in Figure 14 show the results for the existing lead-glass case, and the open circles without the two new improvements in the analysis.

The effect of sectors of the BSPV being blinded by the passage of the incident kaon results in an increase in inefficiency of a factor of four at 20 MeV but is almost invisible at higher energy. This is due to the size of the shower. The open triangles in Fig. 14 indicate the results of MC calculations with 40 layers of Cu/scintillator and no lead glass counter, as depicted in Figure 4.

Having a ring photon veto counter improves the efficiency by another factor of 2–3 at high energy but has almost no effect at 20 MeV for the new case. There is a similar impact (a factor of 2) in the case of old geometry.

Having an upstream photon-veto annular counter helps significantly at high energy; nearly a factor of five for both old and new geometries. However, no significant effects were seen at 20 MeV, which is consistent with Technote K-008.

V. Mechanical Assembly

A. The present scheme

An aluminum cylinder is mounted onto the iron plug to provide a support for the beam counter system and protection to the endcap and collar calorimeters. The B4 assembly is mounted at the end of a semi-circular tray that slides into the upper half of the support cylinder. The tray extends from the target region to the outside of the support cylinder. The light guides of the B4 hodoscope are attached to the tray and fanned out at the supporting flange where they are read by photo-tubes. A lower tray carries the lead-glass photon veto, BeO degrader, and beam wire chamber BWC2

B. New Scheme

The same aluminum support cylinder used in E787 will mechanically support the new beam counter system. The B4 hodoscopes and their associated WLS fibers and 32 phototubes are mounted on an upper semi-cylinder which slides inside the support tube. The BSPV (with its associated WLS fibers and 12 phototubes), BeO degrader and beam wire chamber BWC2 are mounted on a double-walled lower half-cylinder which also slides into the support

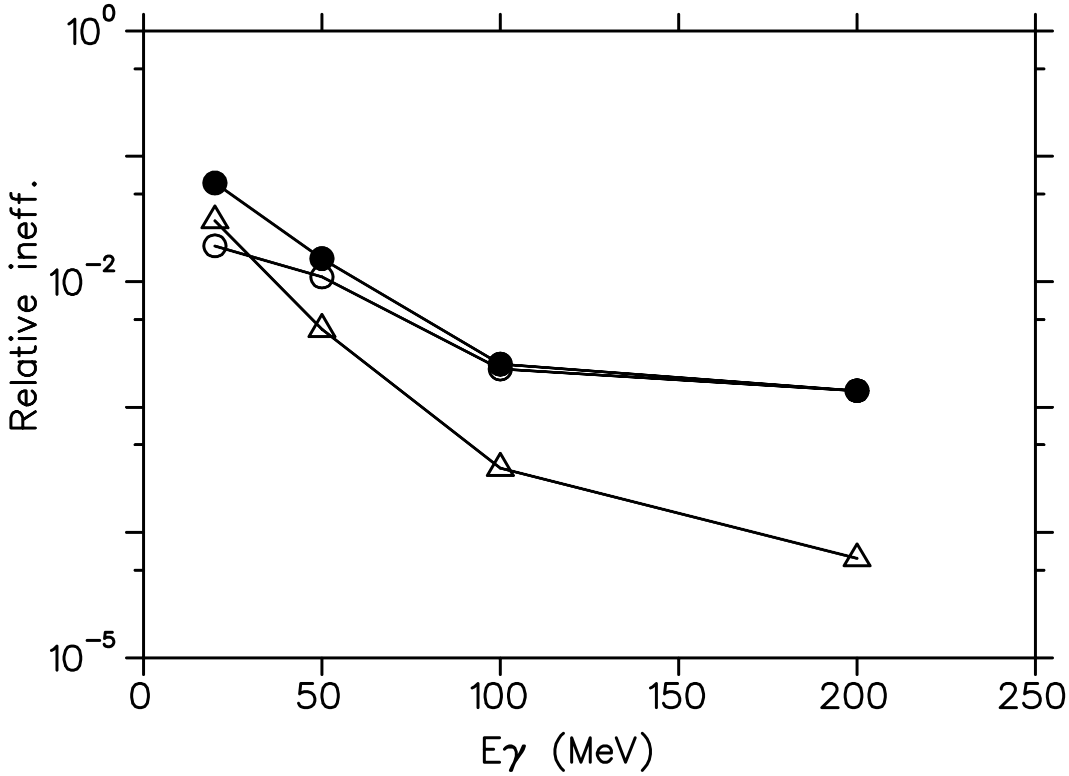

Figure 14: Photon veto inefficiency

tube. Figures 15 and 16 shows the whole mounting scheme.

VI. Proposal for improved beam instrumentation

- We will construct the new B4 with 32 rectangular elements mounted on H3165-10 tubes, as shown in Figures 6,7,8.
- The lead-glass counter will be replaced by a 40-layer Cu/scintillator segmented photon veto(BSPV) with 12 sectors. No ring counter(RPV) near the degrader will be built.
- The upstream photon-veto (UPV)counter will be built and installed
- The layout is shown in Figures 4,5 and 15

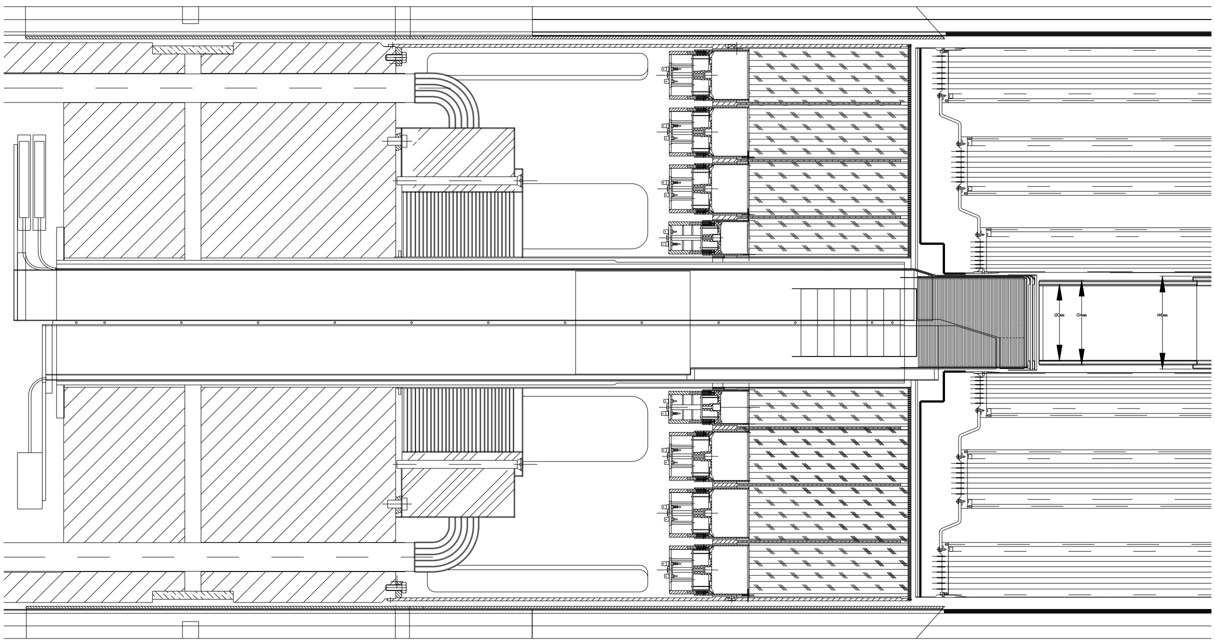

Figure 15: Mechanical assembly,side view

VII. Cost Estimate

Costs shown in Table 5 are in US \$ and are estimated to the nearest one thousand dollars. Labour is costed at \$40per hour.
The total number of extra channels is assumed to be about 32. Photubes already purchased are not included.

VIII. Schedule

A. Construction

Construction of B4 has already begun and will take about 3 months to complete. Construction of the segmented live degrader will start as soon as the design is complete(within 1 month). Once design is complete construction should take about 4 months.The critical-path item is machining pieces of scintillator. Design of the mechanical support is almost complete but depends on the final configuration of the segmented photon veto etc. The old support tube with rail will be used. Construction of mechanical components can proceed in parallel with the other projects, since it must be done in an outside shop. Construction of UPV can proceed later

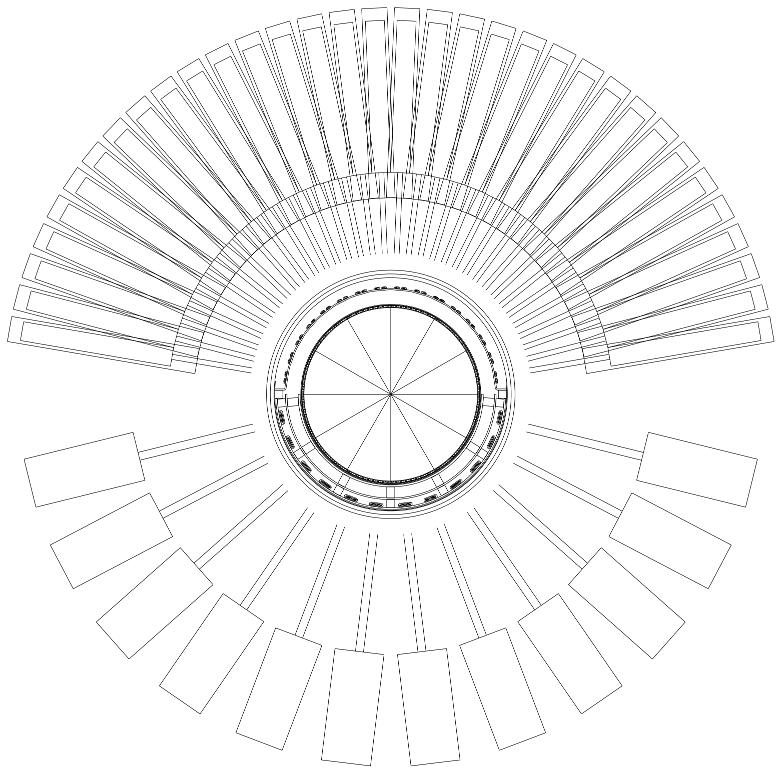

Figure 16: Beam's eye view

B. Installation

When everything is built and tested we will ship it back to BNL. Then the support tube will be inserted and the B4-assembly slid in with the target removed so that we can look from downstream end and shim the support tube to ensure B4 enters UTC without touching anything. Then the B4-assembly is removed, leaving the shimmed support tube in situ. After target installation, we can put back B4 assembly, followed by lower double-walled tube holding remainder of beam instrumentation. After the first time, this should be a relatively painless procedure, once the detector is moved far enough away from the final quadrupole to allow sufficient clearance to insert or remove the beam instrumentation.

Table 6: Cost estimate

Item	Materials	Labour
Detector Construction	15K	20K
HV supplies	5K	
Cables	5K	
TDC (96 ch) x 1	8K	
B4 Disc(16 ch) x 1	2K	
B4 linear FI/FO (4 ch) x4	4K	
Pulse shaping ($30 x 32)	1K	
Total	40K	20K