6. RADIATION SAFETY

6.1 Method

Hadron shielding requirements for the KTEV and KAMI experimental program have been specified according to the requirements of the Fermilab Radiological Control Manual using the methodology of the 1991 Research Division Shielding assessment[52]. The "Cossairt Criteria", appropriately scaled to other energies, intensities, repetition rates, and distances were used to determine beam shielding requirements. The dose rate was assumed to vary

- linearly with the incident beam intensity and repetition rate
- with the beam energy to the 0.8 power
- such that each additional 2.6 feet of earth or concrete reduced the radiation dose by a factor of 10 transverse to the beam direction
- inversely with the square of the distance from the source to the start of the shield

The resulting expression used for the dose rate is

$$H = I*(10^{-3}\ \text{star/cm}^3\ \text{per proton})(10^{-2}\ \text{mrem per star/cm}^3)(0.5/D)^2(E/1000)^{0.8}*10^{-(t/2.6)} \qquad \text{(Eq. 6.1)}$$

where

H	=	dose rate (mrem per spill)
I	=	beam intensity (particles per spill)
D	=	distance from beam line to shield (feet)
E	=	energy (GeV)
t	=	shield thickness (feet of earth)

6.2 Beam Parameters

The assumed parameters of the primary and secondary beams are listed in Table 6.2.1. The effective secondary beam energy was derived from neutron momentum spectra calculated by Coleman using Malensek's standard parametrization of Atherton's data[53]. Differences in the average

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52 Research Division Shielding Assessment - Methodology- 1991

53 A. Malensek, Fermilab Report FN-341 (1981),
Edwards et al., Phys Rev D18, 76 (1981).

energy of the neutron and kaon spectra were ignored, but the *intensity* of neutrals in the secondary beam was assumed to be the sum of the calculated intensities for kaons and neutrons.

The secondary intensity was calculated based on an assumed primary proton energy of 900 GeV, a 45 cm long Be target, a targeting angle of 3.5 milli-radians (vertical) and 0.8 milli-radians (horizontal), a solid angle of 0.4 micro-steradians and two secondary beams. A 3 inch thick Pb photon filter was included in the secondary intensity calculations but Be absorbers were not included after the target since that was considered to be the worst case.

Table 6.2.1

	Energy [GeV]	**Intensity** [ppp]	**Repetition Rate** [hr^{-1}]
Primary Beam	900	$3x10^{13}$ ($5x10^{12}$)	60
Secondary Beam (two beams)	80.5	$1.4x10^{10}$ ($2.3x10^{9}$)	60

KTeV primary and secondary beam parameters for worst-case accident. Intensities in parentheses indicate assumed intensities for normal running.

Note that the shielding requirements listed below for various areas are applicable only to KTeV operations. KAMI operations will require different amounts of shielding in some locations that are discussed later.

6.3 Primary Beam Line Shielding

Primary beam line shielding has been specified assuming the worst-case accident scenario in which the full Tevatron intensity of $3x10^{13}$ protons per spill at 60 spills per hour at 900 GeV is lost in a beam line enclosure or in a buried beam pipe. The design goal was a worst-case accident dose rate of no more than 10 mrem per hour and no use of interlocked radiation detectors. Areas outside this shielding would then require only minimal occupancy and no radiation signs according to the current Radiological Control Manual criteria. To meet this goal at least 19.5 feet of earth-equivalent shielding is required over regions that contain a magnet inside a beam line enclosure, provided the magnet or other loss point is at least one meter from the enclosure wall (Cossairt criteria 2A). For regions containing a buried pipe, at least 21.5 feet of earth-equivalent shielding is required (Cossairt criteria 2C).

A review of shielding assessment drawings for the existing NM2 enclosure shows that 17 feet of shielding currently exist over most of that enclosure decreasing to 15.5 feet toward the north end. This is also sufficient for KTeV primary beam operations provided that four foot fences and high radiation area signs are present. Cossairt category 4A is the relevant one in this case, which has a minimum required thickness of 15.5 feet with a maximum allowed accident rate of 500 mrem per hour and no required use of interlocked detectors.

6.4 Secondary Beam Line Shielding

The amount of shielding required for the secondary beam line was calculated by scaling the Cossairt criteria to the secondary beam effective energy (80.5 GeV) and worst-case accident intensity (1.4×10^{10} neutrals per 3×10^{13} protons). The design goal was a worst-case accident dose rate of no more than 10 mrem per hour and no use of interlocked radiation detectors. Areas outside this shielding would then require only minimal occupancy and no radiation signs according to the current Radiological Control Manual criteria. To meet this design goal at least 8.5 feet of earth-equivalent shielding is required for secondary beam line enclosures that contain beam line magnets or other similar loss points located at least one meter from the enclosure wall, and at least 10.5 feet is required for parts of the secondary beam line that consist only of buried pipe.

6.5 Experiment Hall Shielding

Beam-on hadron dose rates that have been estimated for the KTeV experiment hall design are discussed in this section.

6.5.1 Dose Rates and Shielding Requirements—Transverse Direction

A separate document[54] addresses general KTeV shielding requirements in detail. The design for the KTeV experiment hall most closely resembles the Type I design of the shielding document, a below-grade beam line with an unshielded hall over it and a counting room separated from that hall by a shielding wall sufficient in thickness to allow unlimited occupancy times. The design does not preclude the possible conversion at a later date to a hall more closely resembling the Type II design of the shielding document for KAMI operation. This provision would include the installation of shielding blocks over the entire experiment. One difference in the final design and the Type I hall is that the width of the experiment hall is somewhat smaller than the Type I hall, resulting in higher dose rates at grade level adjacent to the west wall of the hall.

Figure 6.5.1 shows dose rates for KTeV operation calculated at several locations in the experimental hall. The interior of the counting room is adequately shielded for the worst-case accident with dose rates well below 1 mrem per hour. The roof of the counting room adjacent to the east wall of the experiment hall can be divided into two regions, one that is shadowed by the six-foot-thick deck that forms the loading dock inside the experiment hall, and the other that is not. The shadowed region (about one third of the total length of the east wall) has dose rates well below 1 mrem per hour and would allow unlimited occupancy. However, the other two-thirds is not shielded and the calculated worst-case accident dose rates are 159 mrem per hour or 2.6 mrem per spill. If no interlocked detectors are used, the roof of the counting room would require posting as a "High Radiation Area" and fences with locked gates and access by authorized personnel only. If interlocked detectors are used then the calculated dose rate would require posting as a "Radiation Area" and chains or fencing. (Note: The cut-off for the posting requirement is 2.5 mrem per spill, and the calculated number of 2.6 mrem per spill is only slightly greater than this. So small changes in the assumed distance essentially make the whole roof of the counting room less than 2.5 mrem per

54 W. S. Freeman, et al., "Radiation Shielding Requirements for the KTeV Facility, (1/13/93).

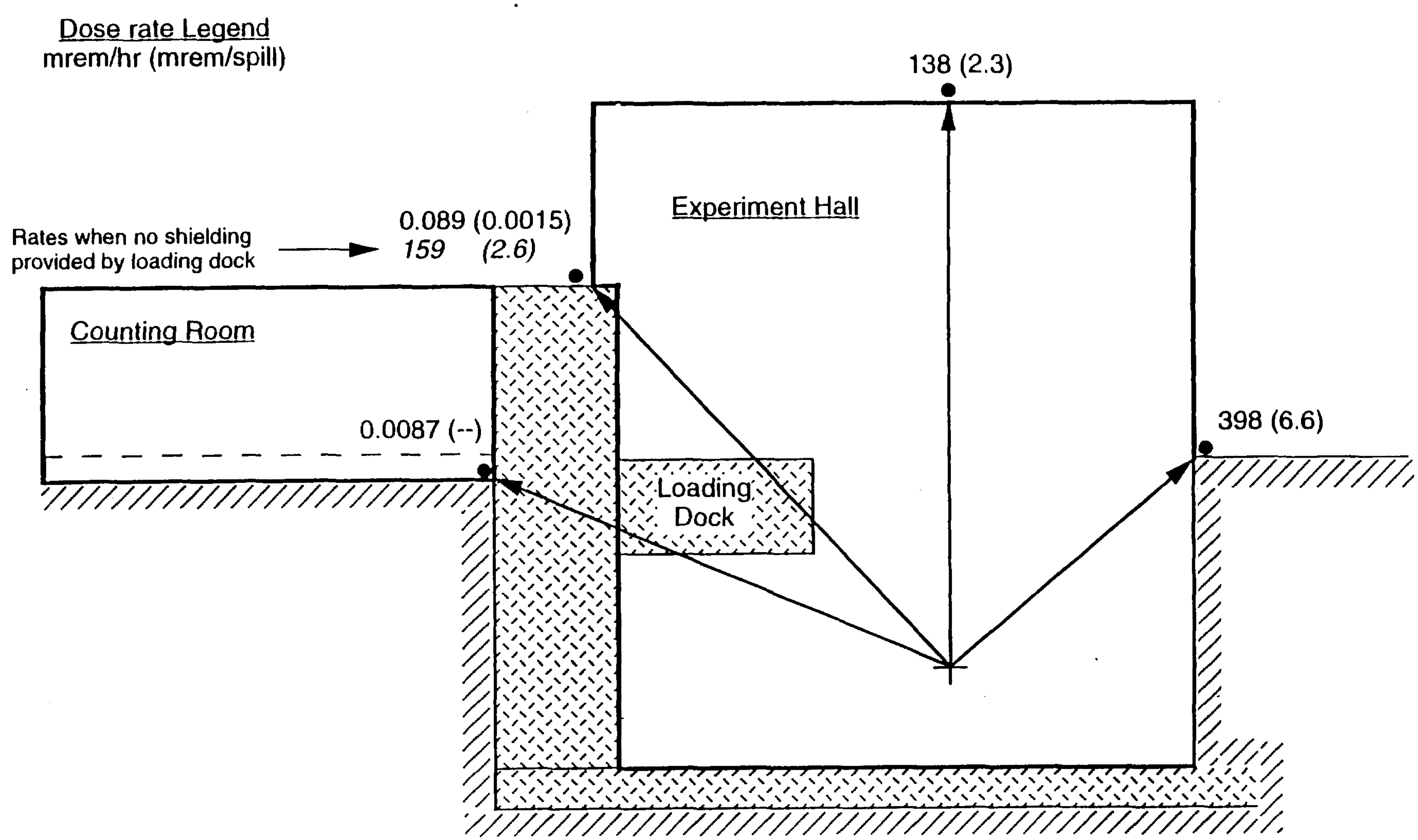


Figure 6.5.1.

Accident Dose Rates For Ktev Running

spill and require only minimal occupancy with no posting requirement, provided dose rates due to normal operation are also acceptable.)

The roof of the experiment hall is slightly farther away from the beam line than the roof of the counting room and so the accident dose rates are slightly less—138 mrem per hour or 2.3 mrem per spill. Without interlocked detectors, the roof would require posting as a "High Radiation Area" and fences with locked gates—access by authorized personnel only. With interlocked detectors, the area would require minimal occupancy and no posting provided dose rates due to normal operations were acceptable. The preferred alternative is to use interlocked detectors and not require posting of the rooftop areas.

The exterior of the building adjacent to the west wall is the place closest to the beam line and subject to the highest accident rates. The worst case accident rates are 398 mrem per hour or 6.6 mrem per spill. If interlocked detectors are not used, then the area adjacent to the west wall would require "High Radiation Area" signs, fences with locked gates, and access by authorized personnel only. If interlocked detectors are used, then the area would require posting as a "Radiation Area" with fencing and minimal occupancy.

The upstream region over the decay enclosure is designed to accomodate future KAMI running involving the transport and targeting of KAMI primary beam in the KTeV decay enclosure. This determines the amount of shielding ultimately required and drives the structural requirements of the decay enclosure. However for consistency, the minimum shielding requirements considering *only* KTeV running are included here (See Section 6.10.2 for KAMI operations). Neglecting the possibility of future KAMI operations and assuming 12 feet from the beam line to the roof of the enclosure as shown in the design, six feet of earth-equivalent shielding is required to give a calculated accident dose rate of 9.6 mrem per hour, which would require only that the berm area be minimally occupied. The 11 feet minimum thickness indicated in the design would allow unlimited occupancy on that part of the berm during KTeV running since the accident dose rate would be about 0.1 mrem per hour.

6.5.2 Dose Rates and Shielding Requirements—Forward Direction

Dose rates at grade level in the forward direction, due both to normal running and accident conditions, were also assessed for the case where no additional shielding is in place over the beam line.

Rates from the Back-Anti (BA)

The dose rates adjacent to the north wall of the experiment hall were calculated with CASIM for normal and accident conditions by modeling the back-anti (BA) neutral beam dump and muon steel downstream using cylindrical approximations to the real geometry. Figure 6.5.2 shows the modeled geometry. An incident neutron beam was assumed. The star density in the downstream soil at a radius corresponding to grade level height (5 meters above the beam) was used to estimate the dose rate using the standard star density-to-dose conversion factor of 10^{-2} mrem/star-cm^{-3}. The results are that the worst-case accident intensity dose rate due to a loss on the BA is 2.6 ± 1.3 mrem per hour and the dose rate at normal operating intensity is 0.4 ± 0.2 mrem per hour.

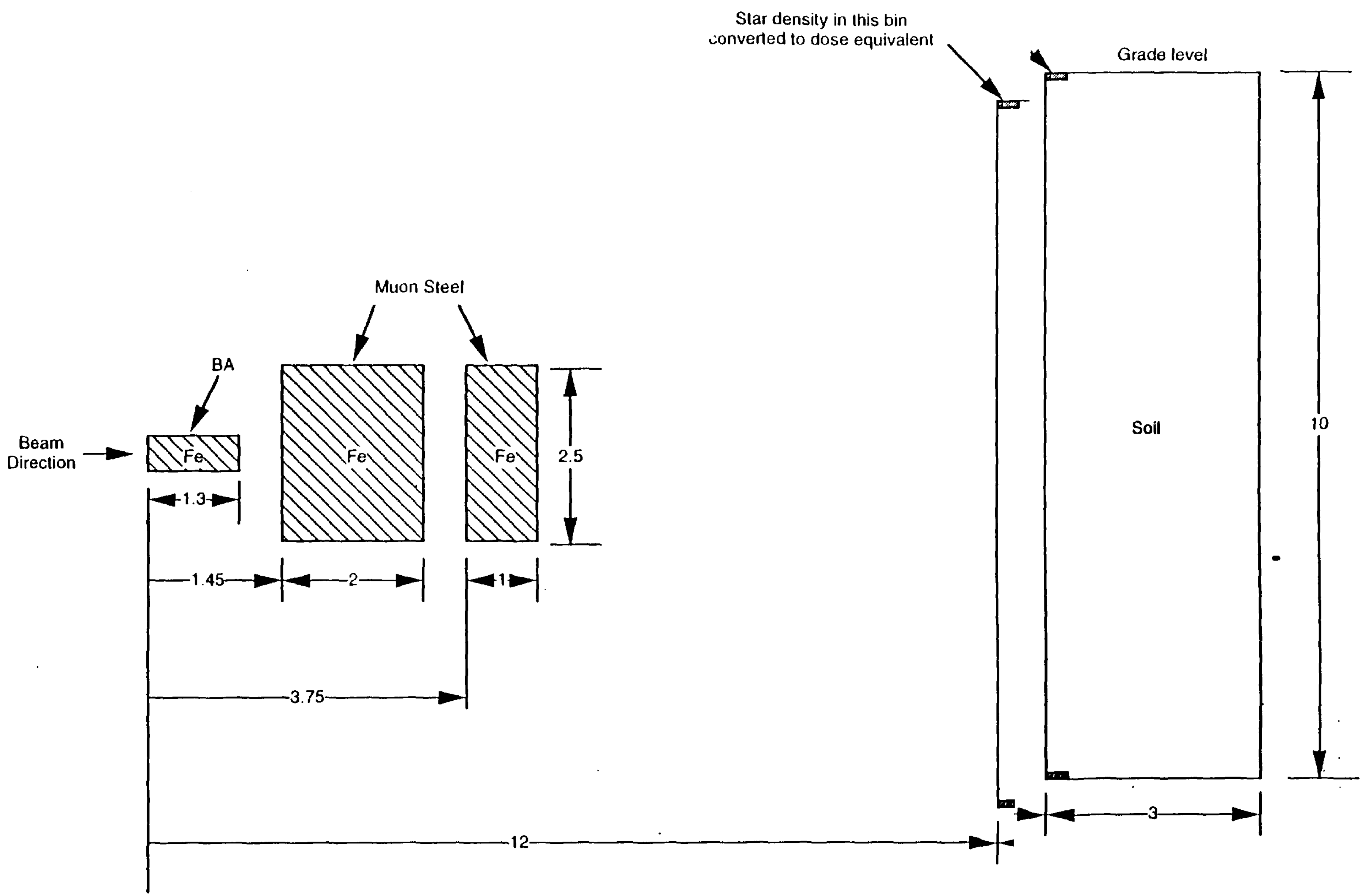


Figure 6.5.2.

CASIM Geometry (cylindrical symmetry)

Dose rate at grade level due to loss on the Back Anti
(all dimensions in meters)

Rates from Accidental Losses Upstream of the BA

The dose rates from accidental beam losses on an object placed in the beam line at three locations were also estimated from CASIM calculations. These rates were calculated to determine the need for any additional forward shielding. The assumed geometry is shown in Figure 6.5.3. Three loss point locations were considered:

i) 2.5 meters upstream of the BA, a distance just sufficient for a line-of-sight to exist directly from the loss point to grade level without passing through any of the muon steel downstream of the BA.

ii) 13.3 meters upstream of the BA, a location corresponding to the center of the most downstream helium bag.

iii) 30.8 meters upstream of the BA, a location at the downstream end of the vacuum decay pipe.

Separate CASIM calculations were done for a hypothetical 30 cm long by 2 cm diameter iron rod placed at each of the three loss points. The maximum star densities in the soil downstream of the hall at grade level were converted to dose equivalents and the results are shown in Table 6.5.1.

Table 6.5.1

Location	Dose Rate[1] (mrem/hour)	Dose Rate[1] (mrem/spill)	Shielding Req'd.- 10 mrem per trip (feet)	Shielding Req'd.- 2.5 mrem per trip (feet)
i	856 (1500)	14.3 (25)	1.5	3.8
ii	758 (1320)	12.6 (22)	3.6	8
iii	580 (1020)	9.7 (17)	3	8.5

1 - No forward shielding is included in these dose rate calculations.
KTeV accident dose rates at grade level in the forward direction for beam losses of 1.4×10^{10} and 80.5 GeV and 60 spills per hour at three loss points in the experiment hall. Assumed loss is on a 30 cm long x 2 cm diameter iron rod. Numbers in parentheses indicate estimated worst case doses based on a 100 cm long rod, as discussed in the text.

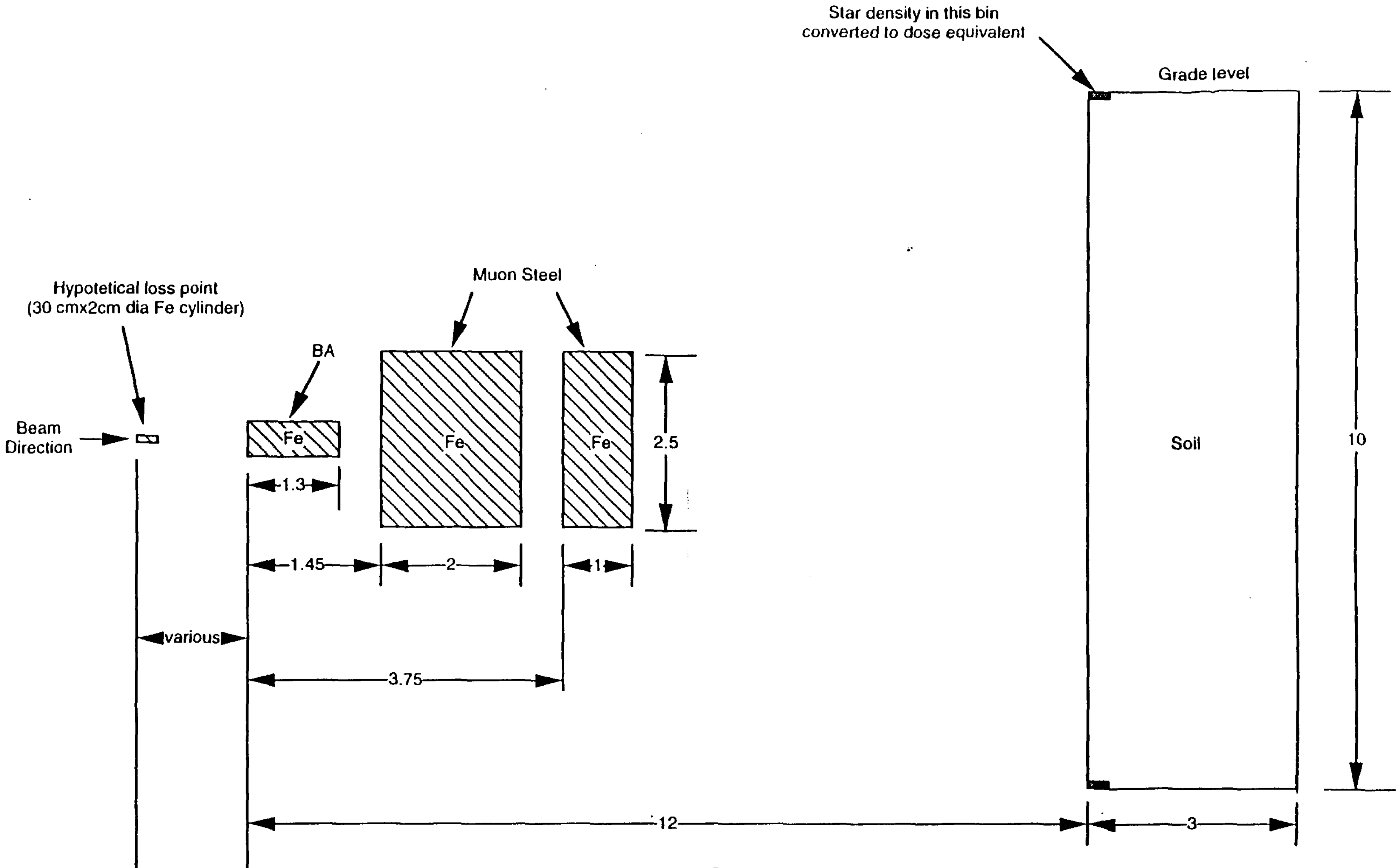


Figure 6.5.3.

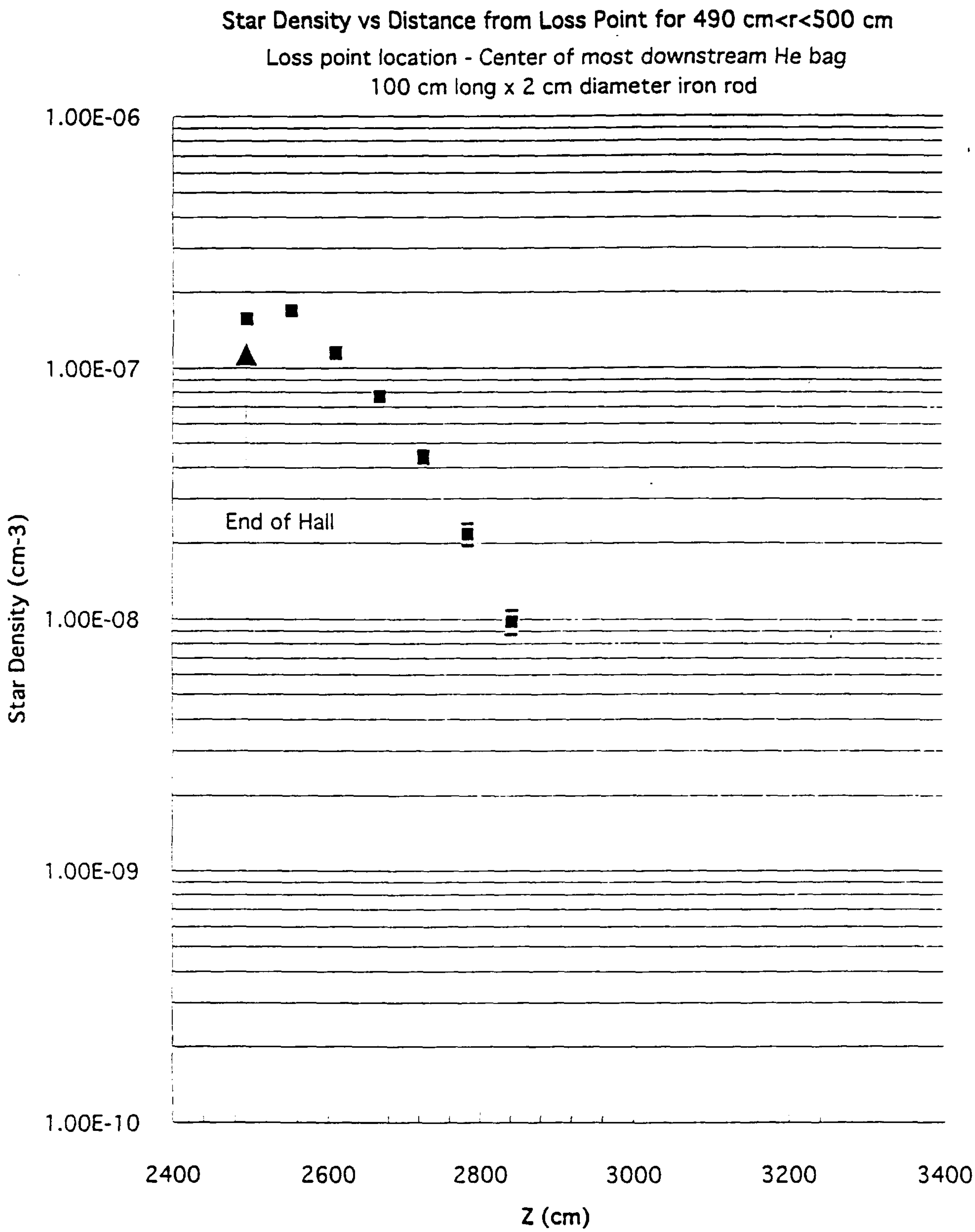
CASIM Geometry (cylindrical symmetry)

Dose rate at grade level due to loss on a hypohetical iron cylinder placed at various location along the beamline (all dimensions in meters)

The effect of changes to the dimensions of the loss point object were also studied at one location (location ii). The effect of an increase in the iron rod length from 30 cm to 100 cm was to increase the calculated dose rate from 12.6 mrem per spill to 22 mrem per spill. An increase in the radius of the 100 cm long rod from 1 cm to 15 cm resulted in a decrease from 22 mrem per spill to 9 mrem per spill. Therefore, the 100 cm long by 2 cm diameter rod was assumed to be the worst case and the calculated dose rates for the 30 cm long rod at locations (i) and (iii) were scaled upward by the factor 22/12.6 and used as worst-case dose estimates. These results are also shown in Table 6.5.1.

Hourly worst-case accident dose rates exceed 1000 mrem per hour, thus interlocked detectors are required. Without additional shielding in the forward direction, the area downstream of the hall would require fences with locked gates and posting as a high radiation area, with fences at the 2.5 mrem per trip boundary. This would interfere with the parking area and HVAC equipment. Thus additional shielding is required in the forward direction to reduce accident dose rates to acceptable values at grade level.

The amount of shielding necessary to attenuate the calculated accident dose rates to an acceptable level was determined from CASIM calculations by looking at the fall off of the star density in the downstream soil. Since this is in the forward direction, the usual factor of ten attenuation for every 2.6 feet of concrete does not apply. A typical attenuation curve in the forward direction obtained from CASIM is shown in Figure 6.5.4. This is taken from the calculation that assumed a loss point at the location of the last helium bag. The figure shows the star density at a fixed radius of 500 cm from the beam line (corresponding to grade level) as a function of the depth into the soil downstream of the hall. To reduce the calculated dose from 22 mrem per trip to 10 mrem per trip requires an attenuation factor of 2.2 which can be achieved with 110 cm (3.6 feet) of soil. To reduce the dose from 22 mrem per trip to 2.5 mrem per trip requires an attenuation factor of 8.8 which can be achieved with 245 cm (8 feet) of soil. A similar analysis was done by looking at the attenuation curves for the other two loss locations to determine the necessary shielding. The results are listed in the last two columns of Table 6.5.1. They show that 8.5 feet of soil (or concrete) in the forward direction, and



Star Density vs Distance from Loss Point for 490 cm<r<500 cm
Loss point location - Center of most downstream He bag
100 cm long x 2 cm diameter iron rod
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
Star Density (cm-3)
End of Hall
2400
2600
2800
3000
3200
3400
Z (cm)

FIGURE 6.5.4.

interlocked detectors, would be sufficient to reduce the accident dose rate from losses at the three locations to 2.5 mrem per trip. The downstream area outside the hall would then require only minimal occupancy with no requirements for signs and ropes/fences. This amount of shielding will be provided by the installation of a six foot thick layer of shielding blocks over the two most downstream bays of the experiment hall.

Rates from the Regenerator

Losses on the active regenerator, located 68 meters upstream of the BA, must also be considered for both the accident case of $3x10^{13}$ and for normal running at $5x10^{12}$ protons on target. In the normal running situation, the regenerator only intercepts one of the two neutral beams at a time. Thus the dose rate will be reduced by a factor of twelve, not six, relative to the accident case.

In the absence of additional shielding, a line-of-sight will exist from the regenerator to a point four feet above grade level at the downstream end of the hall. This line passes over the spectrometer magnet steel and also over the concrete blocks that will be installed over the two downstream bays, so they do not provide any additional shielding in a region from four feet to eight feet above grade level at the north end of the hall.

The dose rates at the downstream end of the hall were calculated using CASIM. The modeled geometry is shown in Figure 6.5.5. It is a cylindrically symmetric geometry, centered on the beam line with the appropriate radial and longitudinal dimensions taken from the hall design. The regenerator loss point was modeled as a two interaction length (76 cm) carbon cylinder 3.8 cm in diameter. (The actual regenerator will be two interaction lengths of plastic scintillator 10 cm on a side). Two CASIM calculations were done. The first was for the case where no additional shielding is provided along the line-of-sight from the regenerator to the downstream end of the hall. The second was for the case where an additional concrete *"regenerator forward shield"* was inserted in a region along the line-of-sight to the downstream end. This shield was three meters in length.

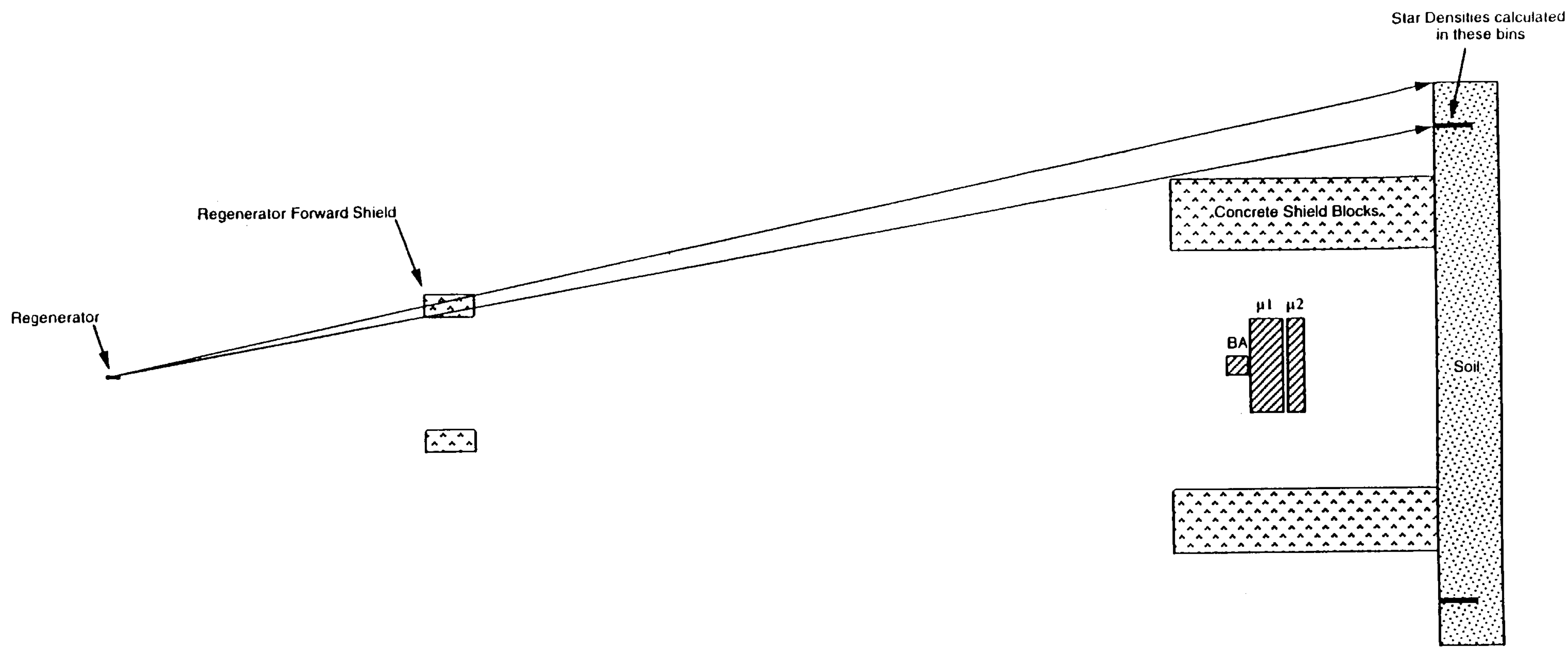


Figure 6.5.5.

Forward Shielding Geometry for CASIM Calculation of Regenerator Shielding

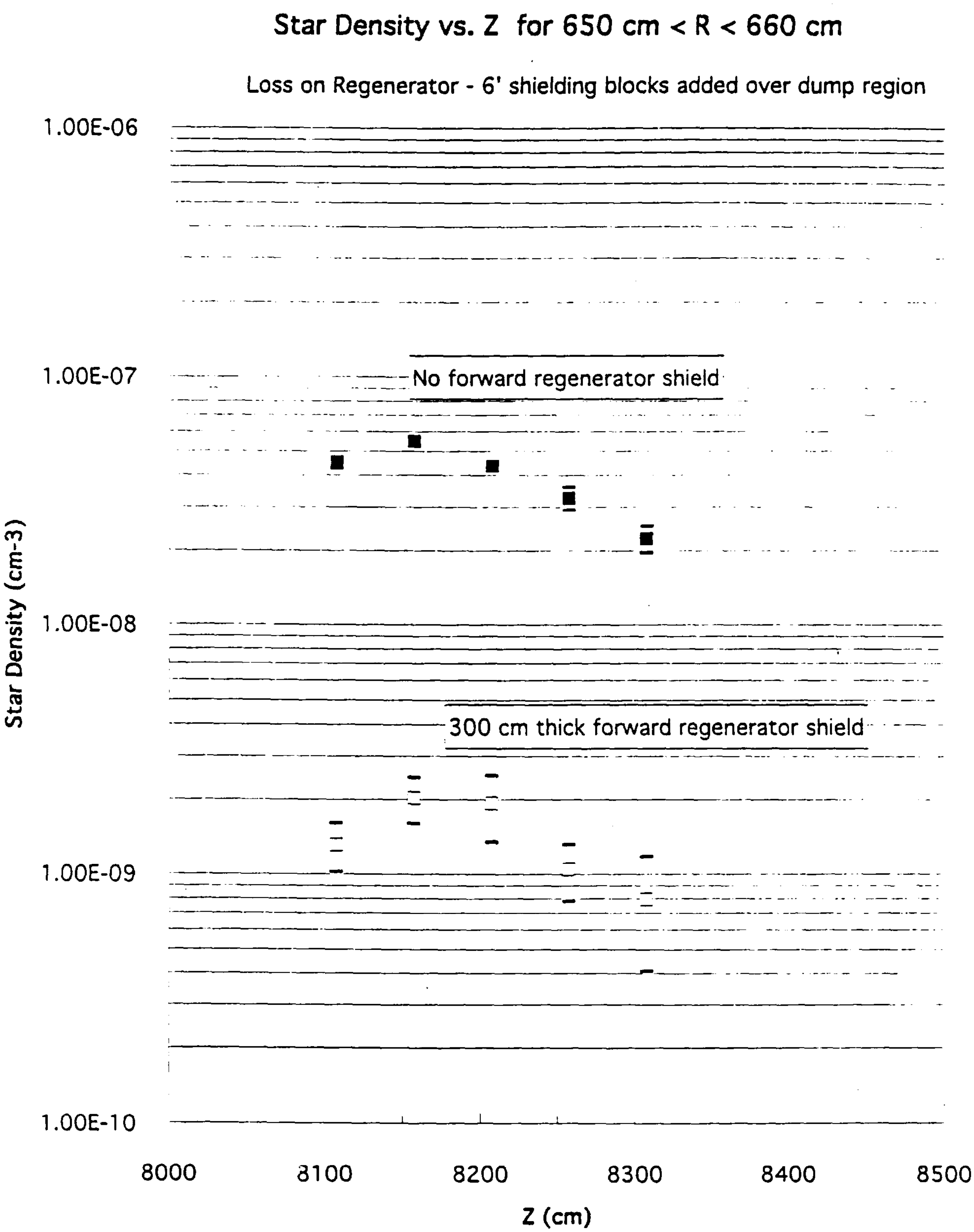
To determine dose rates at the end of the hall, the star density was calculated in five hypothetical soil bins parallel to the beam direction at a radius from the beam line of 6.5 meters, corresponding to a distance of four feet above grade level. Each bin was 50 cm long and 10 cm in radial width. The star density results are shown in Figure 6.5.6 for both forward shielding cases. The addition of the regenerator forward shield reduced the maximum star density by about a factor of 27. The maximum values of star density were converted to dose rates using the standard conversion factor. The results are shown in Table 6.5.2.

TABLE 6.5.2

	Accident Case		**Normal Running**	
	(mrem/hr)	(mrem/spill)	(mrem/hr)	(mrem/spill)
No forward shield	460	8	38	0.6
3 m. thick forward shield	17	0.3	1.4	0.02

Rates at the downstream end of the experiment hall due to interactions in the regenerator. Accident case is 1.4×10^{10} per 3×10^{13}; normal running is 1.2×10^{9} per 5×10^{12}.

If the regenerator forward shielding is not present, then a normal running dose rate of about 38 mrem per hour could exist about four feet above grade level at the downstream end of the experiment hall due to interactions in the regenerator. This would require that the area downstream of the hall be fenced at the 2.5 mrem per hour boundary which would be at a considerable distance from the end wall and interfere with access to the parking area and HVAC equipment. With a 3 meter thick concrete shield, the dose rate from normal running is reduced to 1.4 mrem per hour, and the accident rate is reduced to 0.3 mrem per spill. The normal running rate would only require minimal occupancy downstream of the hall. The accident rate of 0.3 mrem per spill would only require minimal occupancy provided an interlocked detector is installed.



Star Density vs. Z for 650 cm < R < 660 cm
Loss on Regenerator - 6' shielding blocks added over dump region
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
No forward regenerator shield
300 cm thick forward regenerator shield
Star Density (cm-3)
8000
8100
8200
8300
8400
8500
Z (cm)

FIGURE 6.5.6.

Forward Shielding Solution

The combined requirements for shielding in the forward direction can be satisfied by the following steps.

1) Provide at least ten feet of concrete-equivalent along the lines-of-sight from the regenerator to the points between four feet and eight feet above grade at the downstream end of the hall. The width of this regenerator forward shield should be wide enough to shield the entire north wall of the hall with the required ten feet of shielding.

2) Cover the two most downstream bays of the experiment hall with concrete shielding to provide at least the required 8.5 feet along all the lines of sight downstream of the north end of the decay pipe. A six foot layer of shield blocks over the downstream two bays should be sufficient.

3) "Red tag" the decay pipe for configuration control purposes.
4) Install an interlocked detector over the beam line at the downstream end of the hall near grade level to only require minimal occupancy for areas north of the hall.

6.6 Neutron Skyshine

Dose rates due to neutron skyshine have been roughly estimated using an empirical expression for the neutron fluence and simple assumptions about the source strength and effective energy of the skyshine neutrons.

The neutron fluence due to skyshine at a distance, r, from the source is given by

$$\Phi(r) = 2.8Q/(4\pi r^2)[1-\exp(-r/56)]\exp(-r/184.4) \qquad \text{(eq. 6.2)}$$

where Q is the source strength and r is in meters. This expression is thought to be valid for distances greater than 50 meters from the source[55].

To estimate the source strength, it is assumed that one skyshine neutron is emitted per incident particle per GeV of beam energy into 4π solid angle. This is then divided by 2 to get the number emitted into the upper hemisphere.

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55 A.J. Elwyn and J. D. Cossairt, Helth Physics, Vol. 51, No. 6 (1986).

The estimated dose rates due to skyshine assuming effective skyshine neutron energies of 1 MeV and 0.2 MeV are given in Table 6.6.1.

Table 6.6.1

Beam intensity (per spill)	**Source strength,Q** (n/spill)	**Fluence, Φ** @ 50m. (n/cm^2/spill)	**Dose** (mrem/spill)	**Dose** (mrem/hr)
$1.4x10^{10}$	$5.6x10^{11}$	$2.2x10^{3}$	0.073 (0.0036)	4.4 (0.22)

Parameters and dose estimates for skyshine dose rates due to worst case KTeV accidents. Numbers in parentheses are dose rates assuming effective neutron energy of 0.2 MeV

Note that there can be large differences in the estimated rates depending on the effective neutron energy and its corresponding fluence-to-dose conversion factor. These rates are applicable to an unshielded hall. If shielding is present over the loss point then the source strength, Q will have to be reduced by the appropriate amount. For example, with six feet of concrete shielding present over the BA the source strength could be expected to decrease by about a factor of 100, further reducing any dose rate due to skyshine.

6.7 Labyrinths and Penetrations

The attenuations of access labyrinths and penetrations for the KTeV experiment hall were calculated using the formalism of the RD shielding assessment and the associated FORTRAN program developed from that formalism. The results are summarized in Table 6.7.1. The personnel and equipment labyrinth designs, as well as HVAC ductwork, are acceptable for KTeV operation, with accident dose rates at the exits well below 1 mrem per hour, allowing unlimited occupancy at the exits for all but one case. The only exception is the large equipment hatch in NM3 which has a calculated dose rate below 10 mrem per hour and would only require minimal occupancy at the exit. There is an option to install concrete shield blocks similar to the NM2 equipment hatch if required. These shield blocks will be required for KAMI operations with primary beam in the NM3 enclosure as discussed in Section 6.10.6.

The four large-diameter supply and return HVAC ducts at the downstream end of the experiment hall are sufficient in size for a person to enter. Administrative controls will have to be applied to prevent personnel entry (e.g. for maintenance and or repair) while beam is on.

The attenuations of two-legged and single-legged cable penetrations between the experiment hall and the counting room were also calculated and found to be acceptable. Existing cable penetrations associated with the NM beam line enclosures have not yet been re-evaluated for the higher $3x10^{13}$ worst case accident condition, but this is only a modest increase from the $2x10^{13}$ accident intensity of the previous run so it should not have a big impact. They currently are being evaluated as part of a general shielding reassessment for the entire neutrino area.

Table 6.7.1

Labyrinth Location	Number of Legs	Total Attenuation	Dose at Exit (mrem/hr)
NM3 upstream stairwell	4	$1.8x10^{-8}$	$1.4x10^{-5}$
NM3 equipment hatch	2	$2.6x10^{-3}$	2.1
Expt Hall - West side stairwell	2	$2.5x10^{-5}$	$4.1x10^{-3}$
Expt Hall - SE stairwell	3	$3.9x10^{-6}$	$5.9x10^{-4}$
Expt Hall - NE stairwell	3	$6.0x10^{-6}$	$8.9x10^{-4}$
Cable penetrations	2	$1.1x10^{-7}$	$1.3x10^{-5}$
Cable penetrations	1	$1.5x10^{-3}$	0.19
HVAC duct - West supply§	2	$1.2x10^{-4}$	$2.7x10^{-3}$
HVAC duct - West return	4	$1.7x10^{-9}$	$2.9x10^{-7}$
HVAC duct - East supply§	2	$3.8x10^{-4}$	$8.3x10^{-3}$
HVAC duct - East return§	2	$6.5x10^{-5}$	0.015
CsI Supply	4	$2.0x10^{-18}$	0.0
CsI Return	4	$7.4x10^{-13}$	0.0

§ - neglect attenuation of first leg of duct and treat as two-legged duct; but assume off-axis source with distance to mouth equal to length of first duct leg.

KTeV experiment hall labyrinth and penetration attenuations and doses at exits based on worst-case accident loss on-axis of $1.4x10^{10}$ particles per spill at 80.5 GeV and 60 spills per hour.

6.8 Ground Water Protection

The KTeV target station located in the NM2 enclosure has been modeled in CASIM and the levels of ground water activation have be calculated using the single resident well model (SRW).

6.8.1 Description of Modeled Geometry

The modeled target station design included the following components:

a) beryllium target - 40 cm long x 1 cm diameter - similar interaction length to 30 cm long BeO

b) target sweeping magnet (NM2S1) - 381 cm long x 60.8 cm high x 77.4 cm wide with a hole 5 cm high x 4 cm wide on the beam axis

c) copper dump - 452.7 cm long x 20.4 cm wide x 25.4 cm high, with no holes

d) E8/Hyperon magnet (NM2S2) - 548.6 cm long x 181.6 cm high x 291 cm wide, with a hole 0.5 cm high x 3 cm wide on axis

e) steel shielding surrounding the target, sweeping magnet, and copper dump to reduce ground water activation and residual activity

minimum steel thicknesses used:

117.5 cm -	east and west sides of target and NM2S1
124.5 cm -	above target and NM2S1
83.9 cm -	below target and NM2S1
154.9 cm -	east and west of dump
151.1 cm -	above dump
106.7 cm -	below dump

Magnetic fields were not included in the calculations. For simplicity, the targeting angle was assumed to be zero degrees, and no holes were included in the copper dump. The magnets were modeled as simple rectangular blocks of iron with the dimensions given above. The beam height above the floor of the enclosure was 119.4 cm, which determined the maximum amount of shielding that could be added below the beam line. More room existed on the top and sides of the target station components. The southeast corner of the target station iron shielding was beveled to allow a wider passageway into the upstream end of the NM2 enclosure.

The NM2 enclosure was modeled as a concrete-walled enclosure surrounded by dirt out to a radius of 750 cm. The dimensions of the enclosure were taken from the existing construction drawings. The geometry of the modeled target station and enclosure is illustrated in figures 6.8.1 through 6.8.5.

6.8.2 Method and Results

Radioactivity concentrations in ground water must not exceed Environmental Protection Agency (EPA) limits. The EPA limits are derived from the requirement that the concentrations of radioactivity in community drinking water supplies must not result in doses of more than 4 mrem per year to individuals who use that supply as their sole source of drinking water. When only one isotope is present in the water then the 4 mrem per year requirement may be converted into a permissible concentration for that isotope. When more than one isotope is present then the appropriately weighted sum of concentrations must not result in more than 4 mrem per year. Using this criteria, the permissible individual concentrations are 0.4 pCi per ml for Na^{22} and 80 pCi per ml for tritium. However, there exists in addition an explicit regulatory limit of 20 pCi per ml for tritium. So the limits on ground water radioactivity for the case where both Na^{22} and tritium are present can be expressed as two conditions, both of which must be satisfied:

$$\frac{C(H^3)}{80} + \frac{C(Na^{22})}{0.4} \leq 1 \qquad \text{(condition 1)}$$

and

$$\frac{C(H^3)}{80} \leq 1 \qquad \text{(condition 2)}$$

The single resident well model (SRW) was used to calculate the ground water concentrations of tritium and Na^{22}, the principal isotopes of concern. This model assumes that all the radioactivity produced in unprotected soil outside an enclosure in one year is transported to the underlying aquifer and then diluted by 14,600 gallons of water (equal to 40 gallons per day times 365 days). In the SRW model credit is taken for radioactive decay en route to the

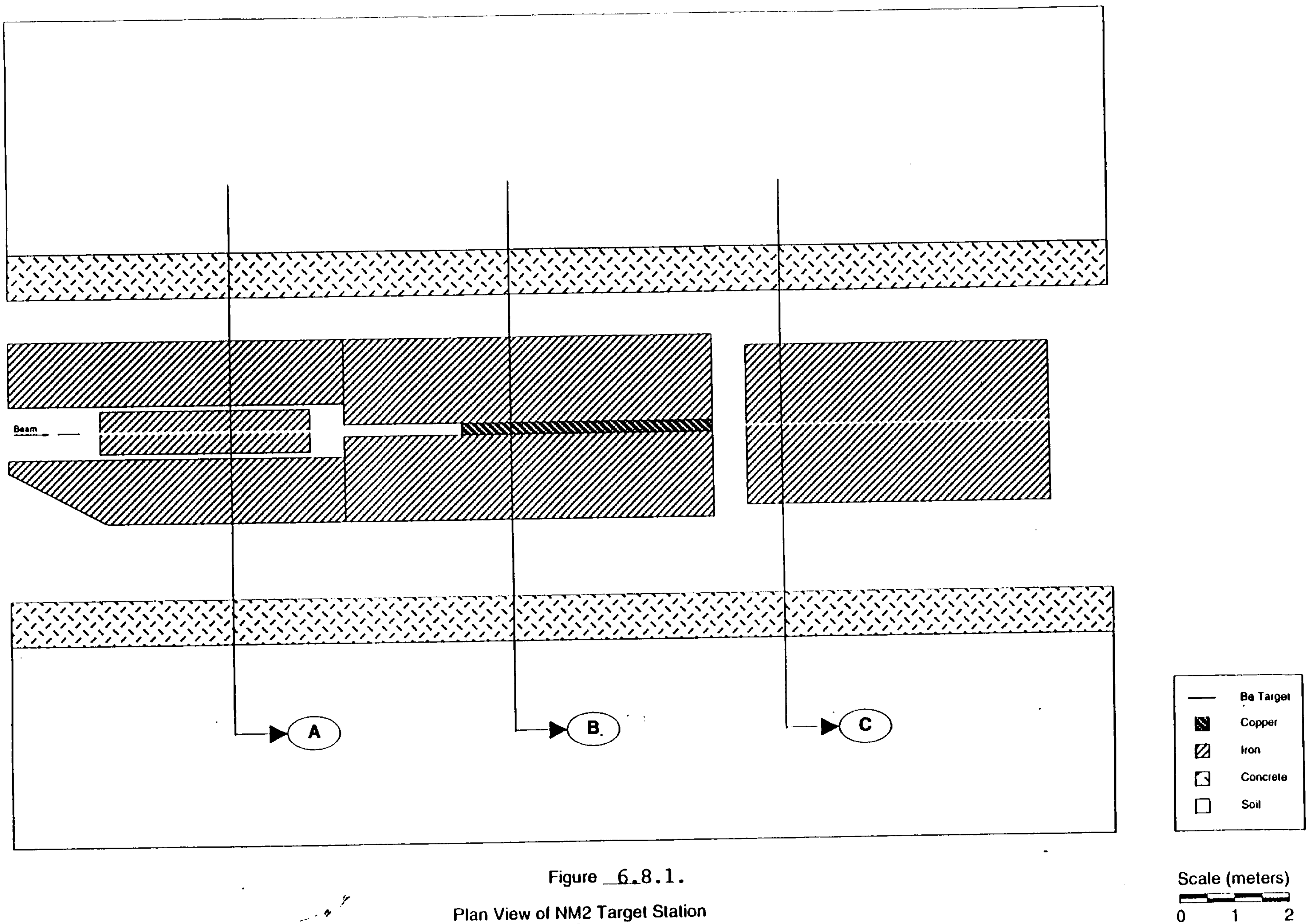

Figure 6.8.1.

Plan View of NM2 Target Station
CASIM Geometry

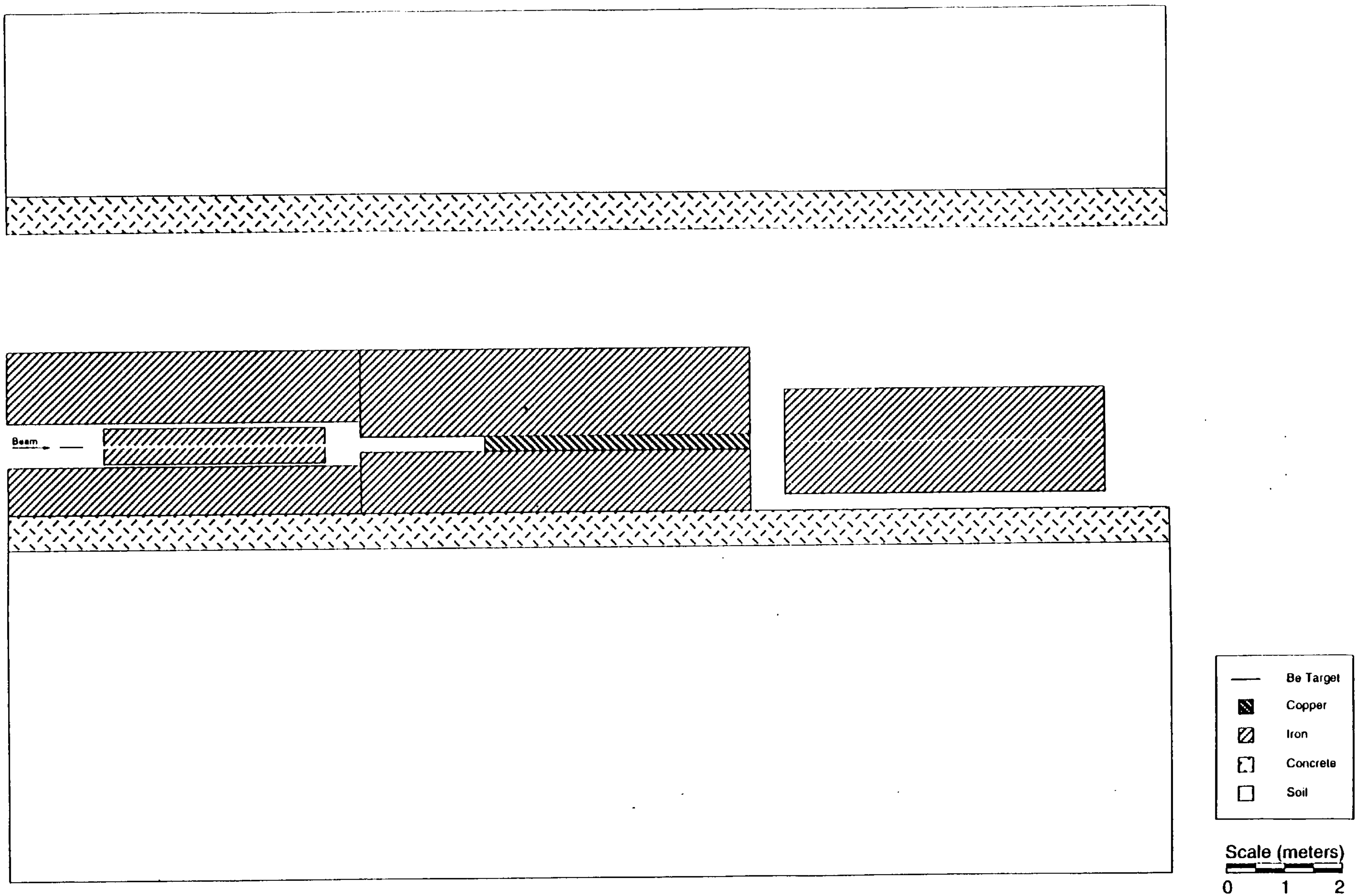

Figure 6.8.2.

Elevation View of NM2 Target Station
CASIM Geometry

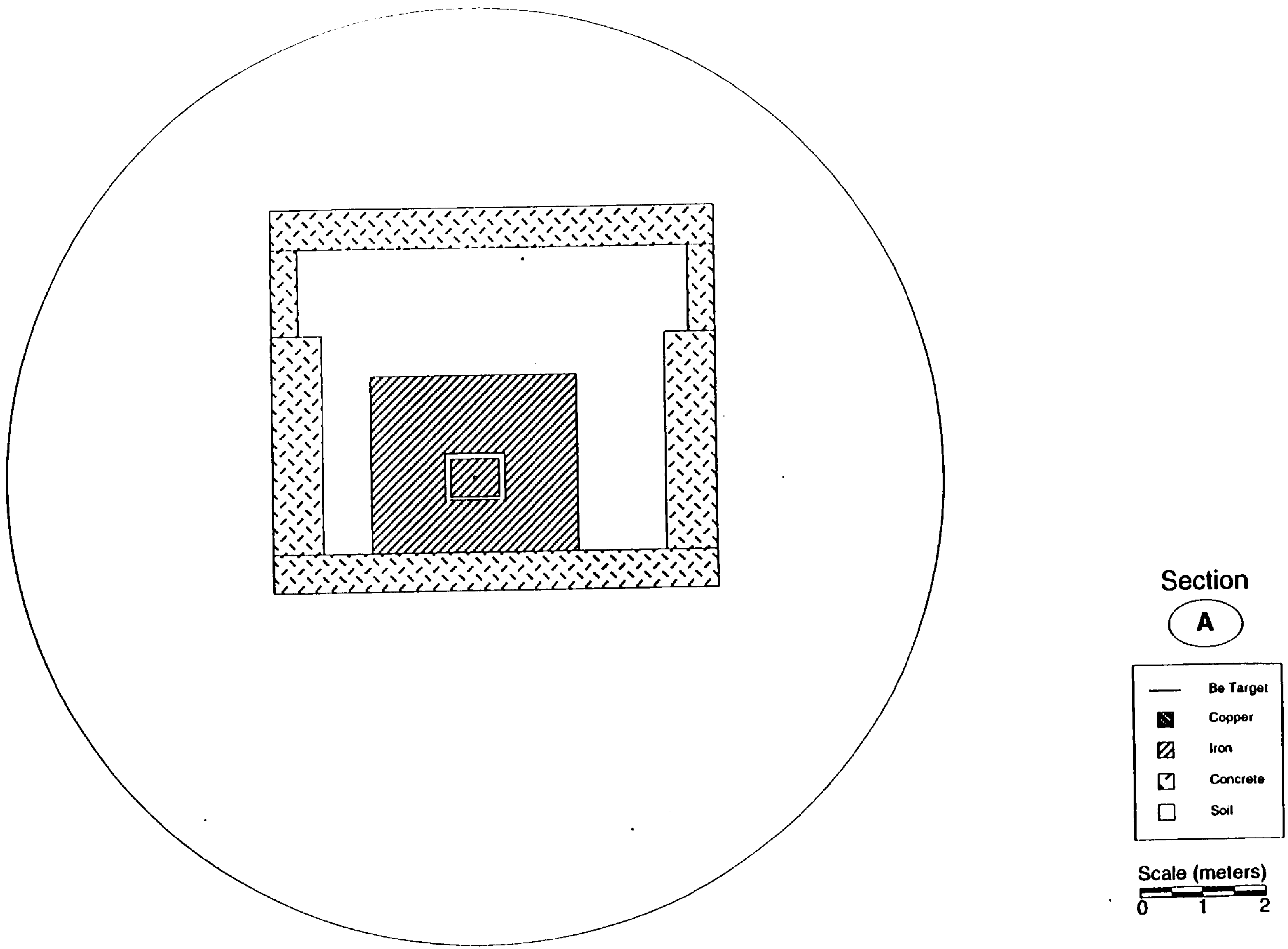

Figure 6.8.3.

Cross Section thru Eartly Dipole
CASIM Geometry

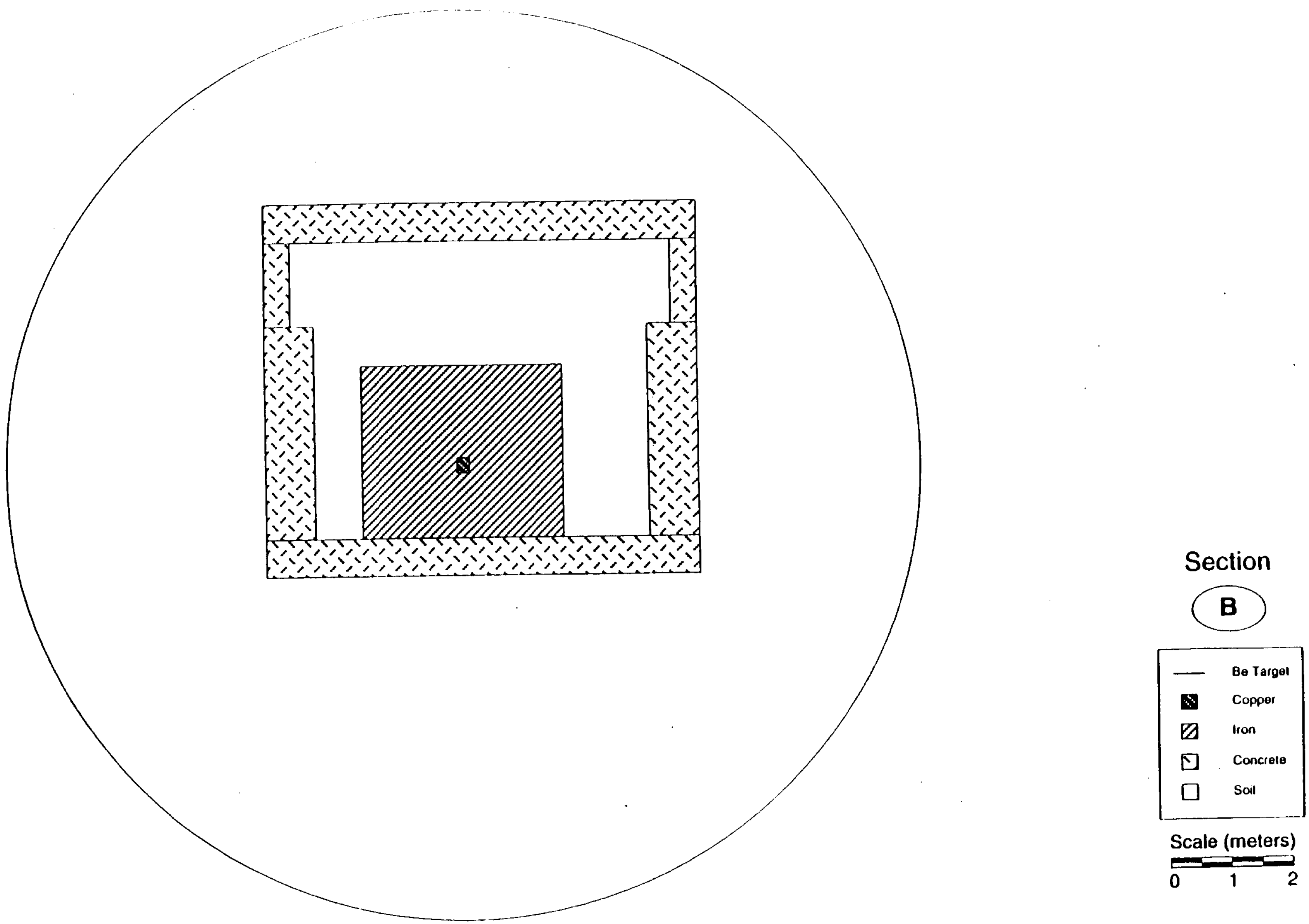

Figure 6.8.4.

Cross Section thru Beam Dump
CASIM Geometry

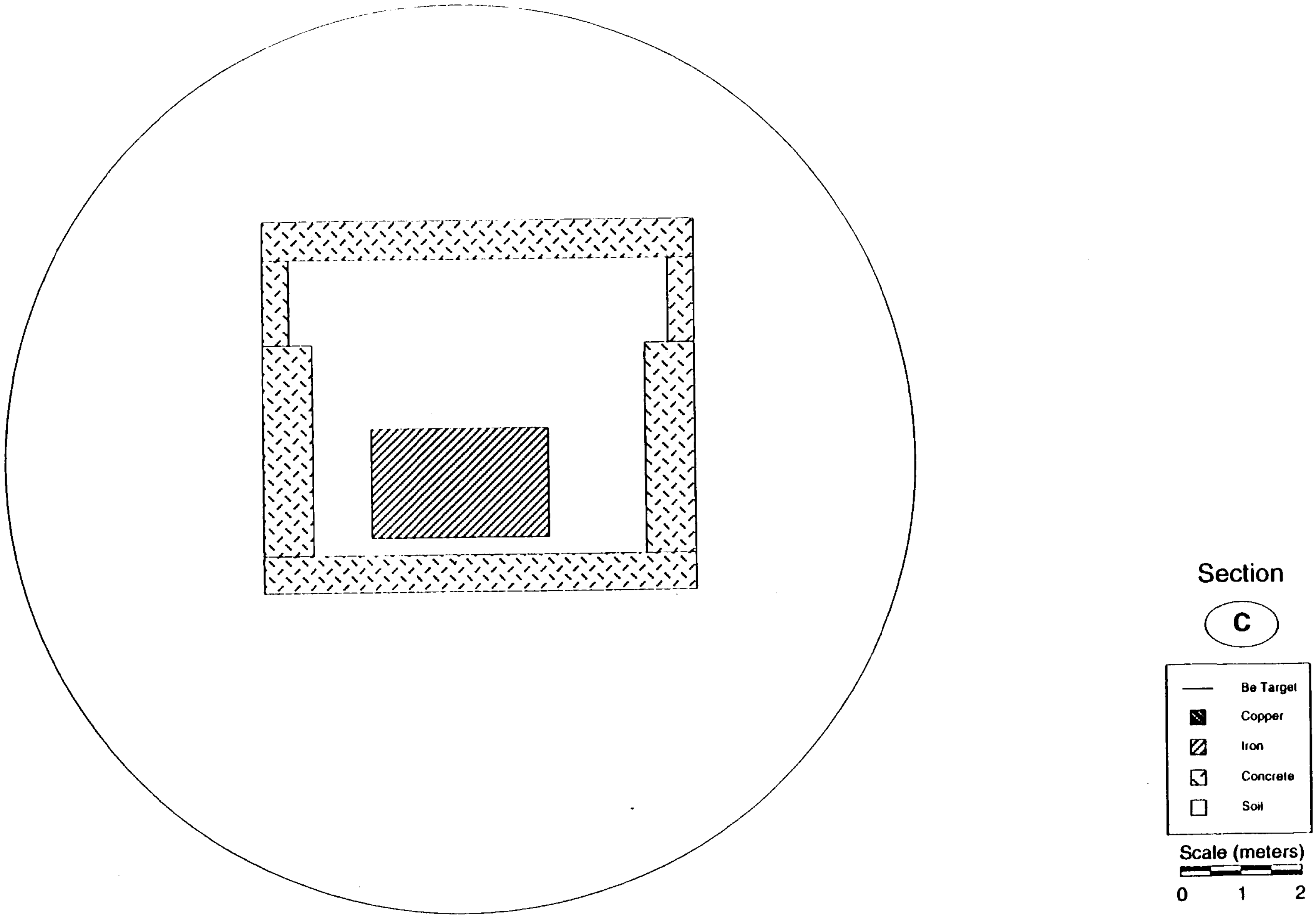

Figure 6.8.5.

Cross Section Thru Hyperon Magnet
CASIM Geometry

aquifer using standard parameters for the rate of movement of tritium and Na^{22} through the soil.

Because of the poor statistics and long execution time, ten CASIM runs for the same geometry were done with different starting seeds. The weighted average of the results from the ten runs was then used to calculate the tritium and Na^{22} activation levels produced in the ground water. See Figure 6.8.6 for the total stars produced for each CASIM run. The average of the ten runs was 1.62×10^{-2} stars per incident proton. The distance to the aquifer was assumed to be 37 feet. The results are shown in Table 6.8.1. Both the ground water radioactivity criteria listed above are satisfied with a safety margin. If the distance to the aquifer is assumed to be zero, (for example if a short circuit pathway to the aquifer existed that negated the possibility of radioactive decay en route) then the criteria are just satisfied.

Table 6.8.1

Stars per incident proton	1.62×10^{-2}	
Protons per year	2×10^{18}	
Distance to aquifer (feet)	37	
	H^3	Na^{22}
Mean lifetime (years)	17.7	3.74
Migration rate (feet per year)	7.5	3.2
Allowed concentrations (pCi per ml)	20	0.4
Leachable atoms per star	0.075	0.003
Calculated concentration (pCi per ml)	1.61	0.02
Ratio to allowed concentrations	0.08	0.05
Condition 1 value <1 ?	0.07 - OK	
Condition 2 value <1 ?	0.08 - OK	

Parameters and results for KTEV primary beam dump ground water activation calculation, assuming no short-circuit pathway to the aquifer.

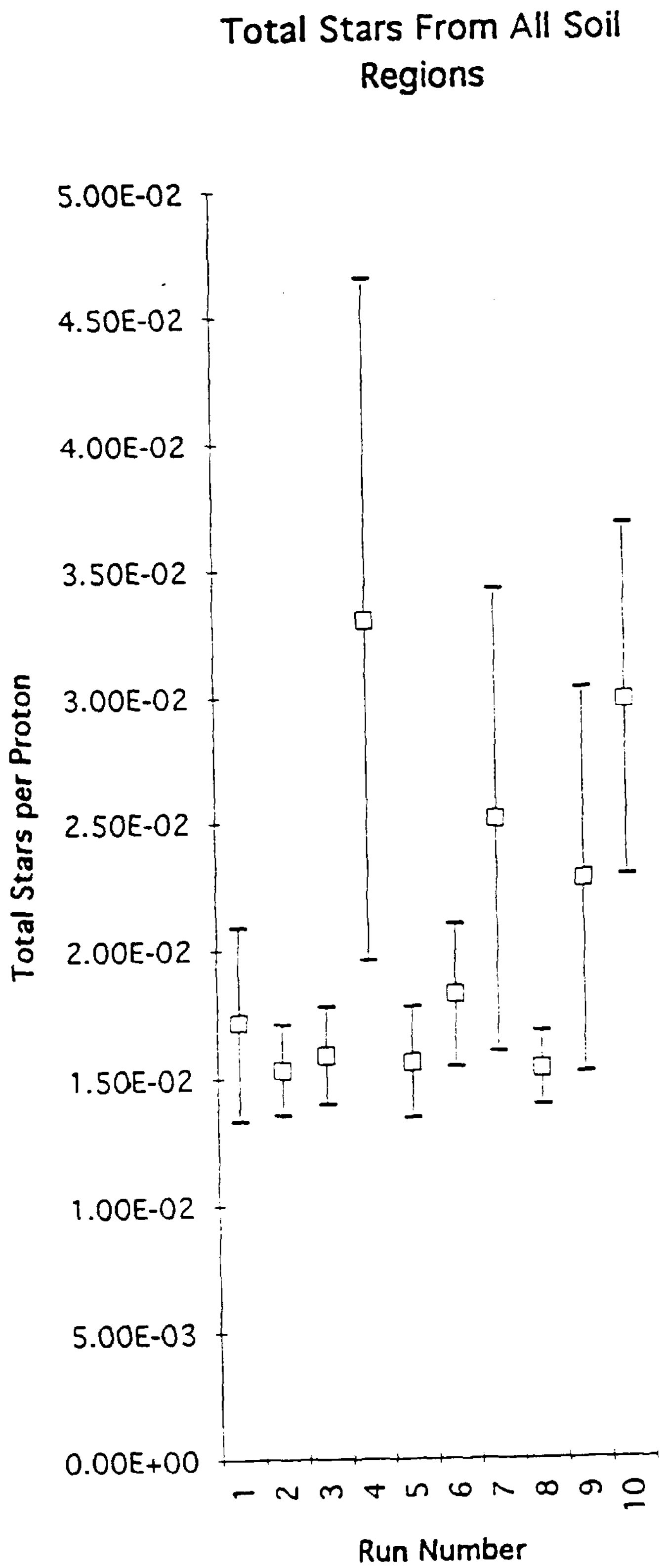
Total Stars From All Soil Regions
5.00E-02
4.50E-02
4.00E-02
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
Total Stars per Proton
1
2
3
4
5
6
7
8
9
10
Run Number

FIGURE 6.8.6.

6.9 Residual Activation of Target Station

Design criteria for dose rates at the external surface of the shielded target station due to residual activation are similar to those used for TeV II target station designs, along with additional constraints imposed by tunnel access issues into NM2. The TeV II criterium is that the worst case dose rate should not exceed 100 mrads per hour at the surface of the shield. This rate was decided upon based on the need for personnel to occasionally access enclosures containing primary target stations without receiving an excessive radiation dose. Of course residual rates for components within the target station shielding will be considerably higher and special precautions will have to be taken for any work involving disassembly of the target station itself.

For an infinite irradiation time followed by no decay time, the dose rate, D, at the surface of a solid iron shield is given by[56]:

$$D = \Omega / 4\pi * \omega(\infty, 0) * S * I$$

where $\omega(\infty,0)$ is the conversion factor, for infinite irradiation and zero cooling, that converts star density at the surface of the shield to dose rate. S is the star density calculated with CASIM, Ω is the solid angle subtended by the source at the measurement location, and I is the beam intensity in protons per second.

Solving for S with

D	=	100 mrads per hour
$\omega(\infty,0)$	=	(9×10^{-3} mrads/hr) per (star/cm^3/sec)
Ω	=	2π
I	=	5×10^{12} per 60 seconds

gives $S=2.7\times10^{-7}$ stars/cm^3.

Star densities less than this value give rates less than 100 mrads per hour for an infinite irradiation and zero cool-off time.

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56 Fermilab Radiological Control Manual, Chapter 13.

An additional issue in NM2 is that the normal access into the enclosure, including the upstream and downstream beam transport tunnels, requires close passage to the primary target station. For this reason, a more substantial target station shield is needed.

The CASIM calculations used for estimating ground water activation can also be used to estimate residual activation levels in the steel shielding. The results are that the dose rate at the bottom of the shield is estimated to be about 128 mrads per hour, the dose rates at the east and west sides are estimated to be about 3.3 mrads per hour and the dose rate on the top surface of the shield is estimated to be about 4.5 mrads per hour. These calculated rates do not consider cool-off time, but also do not consider thin spots in the shield, which are difficult to eliminate. The maximum dose rate is expected to be in the region of the target station that is about 1.6 meters downstream of the start of the copper part of the beam dump, near the maximum in the hadronic cascade in the dump and shielding. Since the bottom of the target station is not accessible to workers entering the enclosure, the dose rate greater than 100 mrads per hour on that surface is acceptable. Residual dose rates to the side and top of the target station should allow viable access without excessive personnel radiation exposure.

6.10 KAMI Operations

Beam parameters for KAMI operation[57], are given in Table 6.10.1.

Table 6.10.1

	Energy (GeV)	**Intensity** (ppp)	**Repetition Rate** (hr^{-1})
Primary Beam	120	$3x10^{13}$ ($3x10^{13}$)	1200
Secondary beam (single beam)	52.8	$1.1x10^{10}$ ($1.1x10^{10}$)	1200

KAMI primary and secondary beam parameters for worst-case accident. Intensities in parentheses indicate assumed intensities for normal running.

57 W. S. Freeman, et al., "Radiation Shielding Requirements for the KTeV Facility (1/13/93).

6.10.1 KAMI Primary Beam Shielding

Scaling the Cossairt criteria to KAMI beam energies and intensities results in the requirement of at least 21 feet of earth-equivalent shielding over a primary beam enclosure in order to have a worst case accident rate of less than 10 mrem per hour. This would result in the area being classified as minimal occupancy, but would not require fences or interlocked radiation detectors (Cossairt criteria 2A). Enclosures with as little as 17 feet of earth-equivalent shielding, posted with high radiation area signs, and protected by four foot fences with locked gates are also acceptable. (Cossairt criteria 4A, accident dose rate less than 500 mrem per hour). The shielding regions over NM2 that currently exist with 15.5 feet and are acceptable for KTeV operation would have to be increased to 17 feet everywhere for KAMI operations.

6.10.2 "Decay Enclosure" (NM3)

During KAMI operations, Main Injector primary beam will be targeted within the NM3 "decay enclosure". This operating mode drives the shielding and structural requirements for the enclosure. KTeV-only running would require substantially less shielding in this area, since only secondary beam will be present for KTeV (see section 6.5.1). The KAMI requirements for this area are the same as those in the previous section, 21 feet of earth equivalent shielding (Cossairt criteria 2A). Note that the actual distance from the beam line to the ceiling is 12 feet rather than the 3 feet assumed in the calculations of the Cossairt criteria, so the dose rate due to an accidental loss on a magnet in this enclosure will be further reduced from the 10 mrem per hour upper limit of category 2A.

6.10.3 KAMI Secondary Beam Shielding

Scaling to KAMI secondary beam energies and intensities, 11.5 feet of earth-equivalent shielding is required to have a worst-case accident of no more than 10 mrem per hour. This would require only minimal occupancy but not require fences or interlocked detectors. (Cossairt Criteria 2A). Enclosures with as little as 7.5 feet of earth-equivalent shielding would be permitted if posted with high radiation area signs and surrounded by 4 foot fences with locked gates (Cossairt criteria 4A).

6.10.4 KAMI Experiment Hall Shielding

Figure 6.13 shows the calculated worst-case accident dose rates at several locations around the experiment hall for the upstream regions of the hall where no shielding is added over the beam line. The counting room is adequately shielded, with dose rates well below the allowed 1 mrem per hour without interlocked detectors. On the roof of the counting room the worst-case accident dose rates are 1780 mrem per hour or 1.5 mrem per spill for the region not shadowed by the six-foot-thick loading dock deck. These rates will *require* the use of interlocked detectors to protect this region, since accident rates above 1000 mrem per hour are not permitted by the Radiological Control Manual. With interlocked detectors the accident dose per spill will require only that the area be minimally occupied, but no other precautions would be necessary. The accident rates are 1 mrem per hour or 0.0008 mrem per spill for the region that is shadowed by the deck, which will be acceptable for a minimal occupancy area with no further precautions even without interlocked detectors, provided dose rates due to normal operations are acceptable.

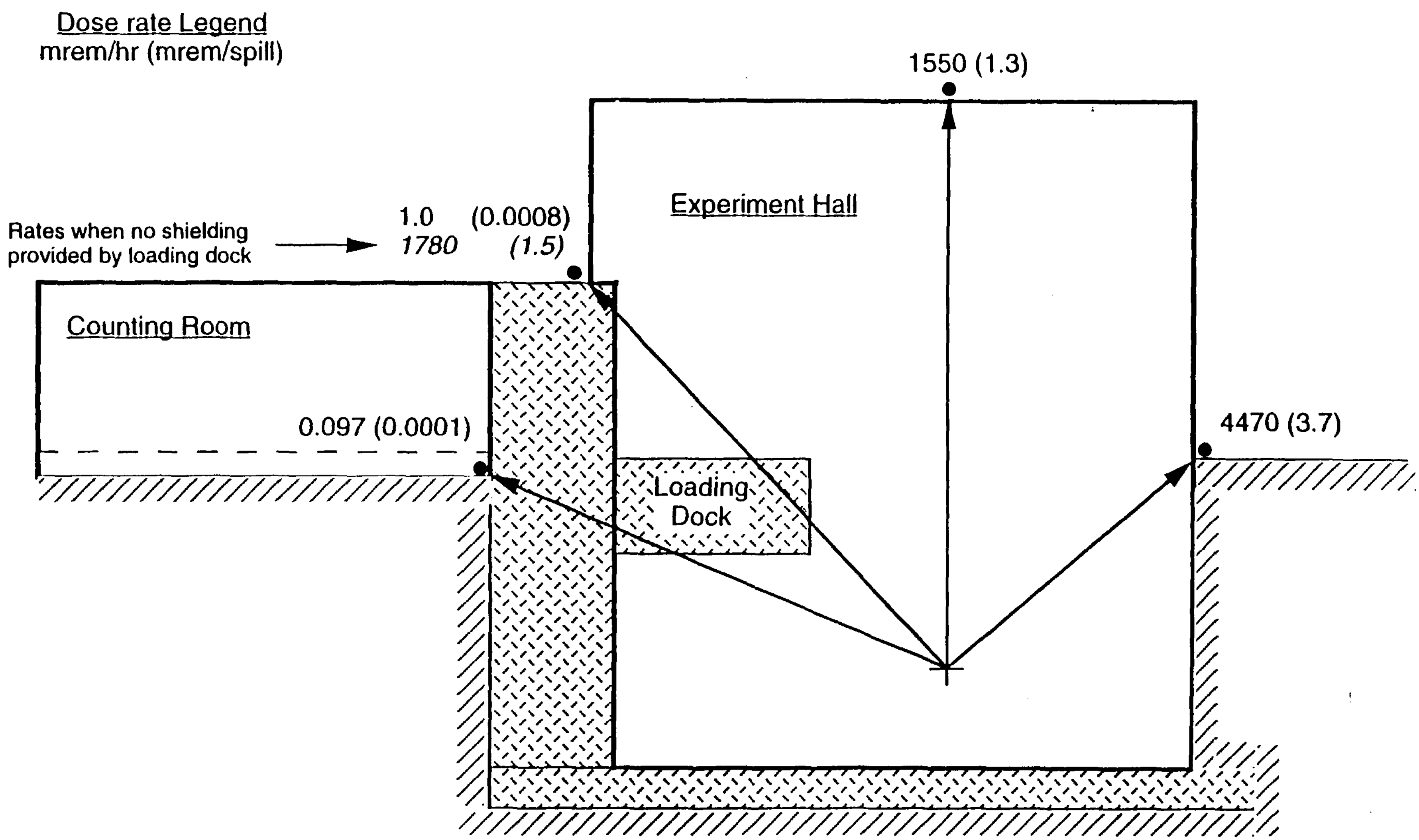

Figure 6.13.

Accident Dose Rate For Kami Running

The roof of the experiment hall has calculated accident dose rates of 1550 mrem per hour or 1.3 mrem per spill. This region also will *require* that interlock detectors be used because the dose rate exceeds 1000 mrem per hour. With interlocked detectors, the roof will be required to be minimal occupancy, with no further restrictions, provided dose rates due to normal operations were acceptable.

The area outside the west wall has calculated accident rates of 4470 mrem per hour or 3.7 mrem per spill. This will also *require* the use of interlocked detectors. Because the dose per spill is between 2.5 and 10 mrem the area will have to be posted as a "Radiation Area" with fencing used to define the boundary, and it will have to be minimally occupied.

Very small fractions of beam loss during normal operations could result in elevated levels of radiation on the roofs of the counting room and experiment hall. For example, a point loss of 1.6×10^{-5} of the normal secondary beam intensity could result in a rate of 0.025 mrem per hour on the roof of the experiment hall. According to the Radiological Control Manual areas with dose rates above 0.025

mrem per hour from normal operations require posting as "Radiologically Controlled Areas", but there is no other restrictions provided the dose rates from normal operations in these minimally occupied areas do not exceed 2.5 mrem per hour and force them into the "Radiation Area" category.

Figure 6.14 shows the calculated worst-case accident dose rates at several locations around the downstream two bays of the hall where six feet of concrete shielding will be added over the experiment. The counting room is adequately shielded, with accident dose rates of 0.1 mrem per hour, well below the allowed 1 mrem per hour without interlocked detectors. On the roof of the counting room the worst-case accident dose rates are 1 mrem per hour or 0.0008 mrem per spill which are acceptable for a minimal occupancy area with no further precautions and do not require interlocked detectors.

The roof of the experiment hall has calculated accident dose rates of 10.2 mrem per hour or 0.0085 mrem per spill. This rate is on the boundary between requiring only minimal occupancy and requiring chains or fencing and posting as a "Radiation Area". In either case interlocked detectors will not be required to protect this area of the roof.

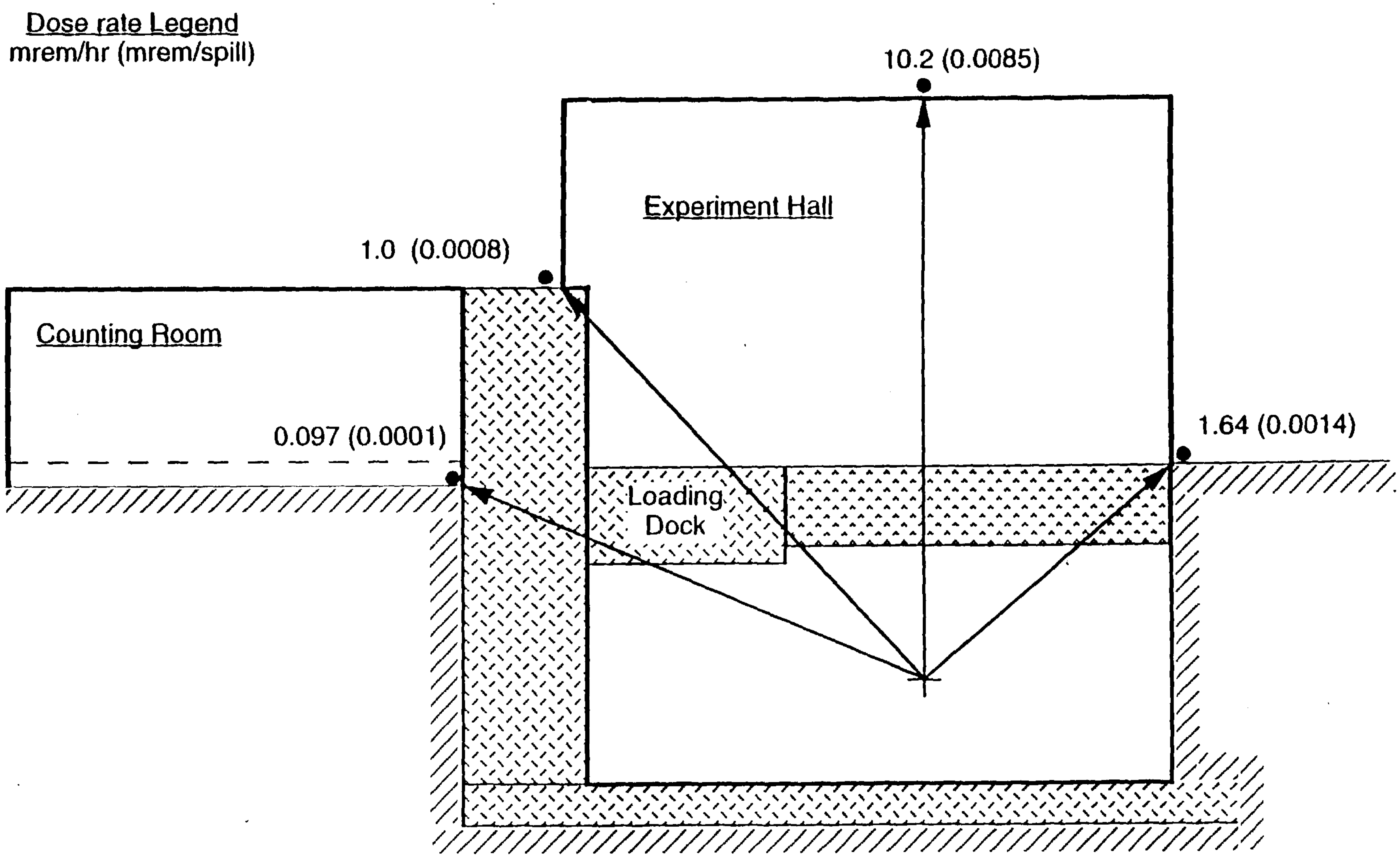

Figure 6.14.

Accident Dose Rates For Kami Running - Shielding Blocks Installed

The area outside the west wall of the experiment hall has calculated accident rates of 1.6 mrem per hour or 0.0014 mrem per spill. This region will require only minimal occupancy and not require interlocked detectors.

6.10.5 Forward Shielding—KAMI

Since the dose per accident spill for KAMI secondary beam is slightly less than that for KTeV, the hadron shielding requirements in the forward direction should also be slightly less. This should be verified by CASIM calculations, which have not yet been done for KAMI secondary beam energy. These calculations should include a study of normal operating rates due to interactions in the neutral beam dump. The forward shielding issue for KAMI may also be affected by the amount of shielding installed downstream of the primary beam dump in the decay enclosure since this may contribute to the downstream dose as well.

6.10.6 Labyrinths and Penetrations

The attenuations of access labyrinths and penetrations in the experiment hall were calculated using the formalism of the RD shielding assessment and the associated FORTRAN program developed from that formalism. The results are summarized in Table 6.10.2.

Table 6.10.2

Labyrinth Location	Number of Legs	Total Attenuation	Dose at Exit (mrem/hr)
NM3 upstream stairwell[1]	4	$1.8x10^{-8}$	0.8
NM3 equipment hatch[1]	2	$2.6x10^{-3}$	$1.2x10^{5}$
Expt Hall - West side stairwell	2	$2.5x10^{-5}$	0.05
Expt Hall - SE stairwell	3	$3.9x10^{-6}$	$6.6x10^{-3}$
Expt Hall - NE stairwell	3	$6.0x10^{-6}$	0.01
Cable penetrations	2	$1.1x10^{-7}$	$1.5x10^{-4}$
Cable penetrations	1	$1.5x10^{-3}$	2.1
HVAC duct - West supply[2]	2	$1.2x10^{-4}$	0.03
HVAC duct - West return	4	$1.7x10^{-9}$	$3.3x10^{-6}$
HVAC duct - East supply[2]	2	$3.8x10^{-4}$	0.09
HVAC duct - East return[2]	2	$6.5x10^{-5}$	0.17
CsI Supply	4	$2.0x10^{-18}$	0
CsI Return	4	$7.4x10^{-13}$	0

1 - primary beam source
2 - neglect attenuation of first leg of duct and treat as two-legged duct; but assume off-axis source with distance to mouth equal to length of first duct leg.
KAMI access labyrinth and penetration attenuations and doses at exits based on worst-case accident loss on-axis of $3x10^{13}$ protons per spill at 120 GeV for primary beam and $1.1x10^{10}$ particles per spill at 52.8 GeV and 1200 spills per hour for secondary beam.

Note that the large NM3 equipment hatch will require the installation of shielding blocks for KAMI running. To reduce the accident dose from $1.2x10^5$ mrem per hour to 10 mrem per hour requires an additional attenuation factor of $8.3x10^5$. This will be provided by a minimum of 11 feet of concrete shielding installed in the hatch. Also, the NM3 upstream personnel labyrinth will have its interlocked door at the top of the stairwell rather than at the bottom as is currently the case for the existing similar labyrinth in NM2. The midstream NM2 interlocked door will also have to be relocated to the top of the stairs to the NS7 Service Building for KAMI operations.

The attenuations and doses at the exits of two-legged and single-legged cable penetrations between the experiment hall and the counting room were also computed for KAMI secondary beam parameters. The results are also given in Table 6.10.2. The two-legged penetration has adequate attenuation for KAMI operations. If a one-legged 10 foot long straight-through penetration design was adopted, the attenuation would be insufficient for a continually occupied space like the counting room, unless interlocked detectors were employed, since the accident dose rate would be 2.1 mrem per hour.

The attenuation and doses at the exits of the four HVAC ducts at the downstream end of the experiment hall and the two CsI house HVAC ducts at the west side of the hall were calculated for KAMI beam parameters. The results are also given in Table 6.10.2. These ducts also provide acceptable attenuations for KAMI operations.

7. SITE AND UTILITY REQUIREMENTS

Modifications to Existing Facilities, Power, and Cooling Requirements

The utility requirements for the magnets in the beamline are listed in Tables 7.1 and 7.2 located in this section.

Modifications to the existing facility to accomodate the listed magnets are minimal. All of the beamline magnets can be supplied water and power from the existing utilities. However, power supplies for the two magnets located in the new construction area will be located in NS7. As part of the new construction package, additional conduit is being installed between NM2 and the new construction to accomodate these power leads. Consequently, there is insufficient conduit capacity for bus work to bring magnet power from NS7 into NM2. Therefore, one additional set of penetrations are required between NS7 and NM2. Specifically, the penetrations are for 6 pair of watercooled bus from NS7 north to the access hatch, coring through the hatch and running the bus down the west wall of the hatch, then along the corridor ceiling into NM2 high bay where 3 pair will go upstream and 3 pair will go down stream. Of the 3 pair of Bus that go down stream, one pair stops in NM2, one pair goes to NM3 and the third pair goes to NM4.

Radiation safety personnel are looking at that routing to see if the gap the bus would create where it comes down the hatch is a problem. If not, we would not need any additional penetrations. If so, we will need to install penetrations for all 6 pair of bus plus a couple spares. These penetrations are 5" by 7" structural steel.

The existing LCW capacity in NS7 is sufficient to accomodate all of the power supplies located in that building for KTeV. Additionally, the LCW in NM2 is sufficient to serve all of the beamline magnets in NM2. LCW for the magnets in the experimental hall is going to be fed via new LCW supply and return piping from NS2 as part of the new construction. This same new supply and return completes the LCW loop which services NS7.

Alignment and survey techniques used to achieve the necessary precision will require some modifications to the existing NM2 facility for alignment site risers and monuments. These requirements are specified in Chapter 9.

Table 7.1
KTeV Magnet Power Requirements

Item	Description	Max. Current (DC amps)	Voltage	B Field (kilogauss or kG/in)	Power (kilowatts)	Power Supply
Pretarget						
NM1BPM1	Horizontal beam position monitor	NA	NA	NA	NA	NA
NM1BPM2	Vertical beam position monitor	NA	NA	NA	NA	NA
NM1WC1	Vacuum bayonet SWIC 1mm	NA	NA	NA	NA	NA
NM1U-1	Vertical bend EPB 5-1.5-120	1688	29.5	15.0	50	TR500
NM1U-2	Vertical bend EPB 5-1.5-120	1688	29.5	15.0	50	TR500
NM1H	Trim Horiz.. 4-4-30	180	50.0	4.0	9	PEI 20
NM2BPM1	Horizontal beam position monitor	NA	NA	NA	NA	NA
NM2BPM2	Vertical beam position monitor	NA	NA	NA	NA	NA
NM2WC1	Vacuum bayonet SWIC 1mm	NA	NA	NA	NA	NA
NM2SEM	Removeable intensity monitor	NA	NA	NA	NA	NA
NM2EU-1	Main Ring B2 4-2-240	4750	34.0	17.9	162	TR500
NM2EU-2	Main Ring B2 4-2-240	4750	34.0	17.9	162	TR500
NM2V	Trim Vert. 4-4-30	180	50.0	4.0	9	PEI 20
NM2Q1-1	Focus 4Q120	1175	42.8	5.5	50	TR240
NM2Q1-2	Focus 4Q120	1175	42.8	5.5	50	" " "
NM2Q1-3	Focus 4Q120	1175	42.8	5.5	50	" " "
NM2Q2-1	Defocus 4Q120	1175	42.8	5.5	50	TR240
NM2Q2-2	Defocus 4Q120	1175	42.8	5.5	50	" " "
NM2Q2-3	Defocus 4Q120	1175	42.8	5.5	50	" " "
NM2Q2-4	Defocus 4Q120	1175	42.8	5.5	50	" " "
NM2D1-1	AVB 1 - B2 4-2-240	4750	34.0	17.9	162	TR500
NM2D1-2	AVB 2 - B2 4-2-240	4750	34.0	17.9	162	" " "
NM2D2	AVB 3 - B2 4-2-240	4750	34.0	17.9	162	" " "
NM2H	Trim Horiz. 4-4-30	180	50.0	4.0	9	PEI 20
NM2WC2	Target SWIC	NA	NA	NA	NA	NA
NM2WC3	Target SWIC	NA	NA	NA	NA	NA
Target Pile/Sec. Beam						
NM2WALL	Upstream end of target hall					
NM2TGT	30 cm BeO target	NA	NA	NA	NA	NA
NM2S1	Eartly sweeper	1500*	29.0	20.0	44	PEI500
NM2BD	Dump	NA	NA	NA	NA	
NM2S2	E8 hyperon magnet - µsweep1†	1500*			500	TR500
NM2AB1	Common absorber	NA	NA	NA	NA	NA
NM2AB2	Moveable absorber	NA	NA	NA	NA	NA
NM2TCOL	Primary collimator	NA	NA	NA	NA	NA
NM2S3	Muon spoiler - µsweep2	1200*	116.0	18.9	139	TR240
NM2SR	Modified B2 4-4-240	4750	34.0	12.0	162	TR500
NM2CV1	Slab Collimator	NA	NA	NA	NA	NA
NM2BS	Beamstop	NA	NA	NA	NA	NA
NM2CH	2-jaw collimator	NA	NA	NA	NA	NA
NM2CV2	2-jaw collimator	NA	NA	NA	NA	NA
NM2BP	beam pipe(s)	NA	NA	NA	NA	NA
NM3CVH	Defining collimator	NA	NA	NA	NA	NA
NM3S	Argonne 10-4-72	3000	145.0	20.6	435	TR500
NM3BP1	18" beam pipe	NA	NA	NA	NA	NA
NM3BP2	30" beam pipe	NA	NA	NA	NA	NA
NM3BP3	48" beam pipe	NA	NA	NA	NA	NA
NM4AN	Spectrometer magnet#	2344*	342.0	550MeV/c	802	2-PEI500
# Nominal = 1919 A, 537 kW, 450 MeV/c		**Total Max. DC Magnet Power**			**3371**	
* DC only. † Rough est.	**Estimated Nominal Operating Power (with ramping)**				**1895**	

Table 7.2
KTeV LCW Requirements

Item	Description	LCW Flow (gpm)	Temp. Rise (degrees F)	Pressure Drop (psi)	Load (kilowatts)	Power Supply
Pretarget						
NM1BPM1	Horizontal beam position monitor	NA	NA	NA	NA	NA
NM1BPM2	Vertical beam position monitor	NA	NA	NA	NA	NA
NM1WC1	Vacuum bayonet SWIC 1mm	NA	NA	NA	NA	NA
NM1U-1	Vertical bend EPB 5-1.5-120	4.7	80	100	50	TR500
NM1U-2	Vertical bend EPB 5-1.5-120	4.7	80	100	50	TR500
NM1H	Trim Horiz.. 4-4-30	6.4	50		9	PEI 20
NM2BPM1	Horizontal beam position monitor	NA	NA	NA	NA	NA
NM2BPM2	Vertical beam position monitor	NA	NA	NA	NA	NA
NM2WC1	Vacuum bayonet SWIC 1mm	NA	NA	NA	NA	NA
NM2SEM	Removeable intensity monitor	NA	NA	NA	NA	NA
NM2EU-1	Main Ring B2 4-2-240	16.4	65	200	162	TR500
NM2EU-2	Main Ring B2 4-2-240	16.4	65	200	162	TR500
NM2V	Trim Vert. 4-4-30	6.4	50		9	PEI 20
NM2Q1-1	Focus 4Q120	8.0	45	100	50	TR240
NM2Q1-2	Focus 4Q120	8.0	45	100	50	" " "
NM2Q1-3	Focus 4Q120	8.0	45	100	50	" " "
NM2Q2-1	Defocus 4Q120	8.0	45	100	50	TR240
NM2Q2-2	Defocus 4Q120	8.0	45	100	50	" " "
NM2Q2-3	Defocus 4Q120	8.0	45	100	50	" " "
NM2Q2-4	Defocus 4Q120	8.0	45	100	50	" " "
NM2D1-1	AVB 1 - B2 4-2-240	16.4	65	200	162	TR500
NM2D1-2	AVB 2 - B2 4-2-240	16.4	65	200	162	TR500
NM2D2	AVB 3 - B2 4-2-240	16.4	65	200	162	" " "
NM2H	Trim Horiz. 4-4-30	6.4	50		9	PEI 20
NM2WC2	Target SWIC	NA	NA	NA	NA	NA
NM2WC3	Target SWIC	NA	NA	NA	NA	NA
Target Pile/Sec. Beam						
NM2WALL	Upstream end of target hall					
NM2TGT	30 cm BeO target	NA	NA	NA	NA	NA
NM2S1	Eartly sweeper - RAW water	9.0	33	90	44	PEI500
NM2BD	Dump - RAW water	60.0			22	
NM2S2	E8 hyperon magnet - µsweep1	50.0			500	TR500
NM2AB1	Common absorber	NA	NA	NA	NA	NA
NM2AB2	Moveable absorber	NA	NA	NA	NA	NA
NM2TCOL	Primary collimator	NA	NA	NA	NA	NA
NM2S3	Muon spoiler - µsweep2	19.0	49	150	139	TR240
NM2SR	Modified B2 4-4-240	16.4	65	200	162	TR500
NM2CV1	Slab Collimator	NA	NA	NA	NA	NA
NM2BS	Beamstop	NA	NA	NA	NA	NA
NM2CH	2-jaw collimator	NA	NA	NA	NA	NA
NM2CV2	2-jaw collimator	NA	NA	NA	NA	NA
NM2BP	beam pipe(s)	NA	NA	NA	NA	NA
NM3C	Defining collimator	NA	NA	NA	NA	NA
NM3S	Argonne 10-4-72	45.0	60	185	435	TR500
NM3BP1	18" beam pipe	NA	NA	NA	NA	NA
NM3BP2	30" beam pipe	NA	NA	NA	NA	NA
NM3BP3	48" beam pipe	NA	NA	NA	NA	NA
NM4AN	Spectrometer magnet#	172.0	39	200	802	2-PEI500
	Est. Total LCW Flow	**538**		**Max. DC Load**	**3393**	
# Nominal = 1919 A, 537 kW, 450 MeV/c			**Est. Nominal Operating Load (with ramping)**		**1917**	

8. INSTALLATION

Constraints impacting the beamline component installation include the 20 ton capacity of the existing NM2 crane, the 10'-6" crane maximum hook height, the size of the NM2 equipment hatch, and clearence between the installed components and the NM2 building walls. All of the above constraints have been understood during the design efforts for each individual component.

Specific installation sequencing requirements are:

1. Existing NM2 target pile must be completely removed because of insufficient staging space in the Target Hall.
2. The steel for Mu-Sweep II [NM2S3] must be placed in the downstream end of NM2 prior to installing the Target Pile and E-8 magnet.
3. It is preferred that the beamline elements upstream of the Target Pile be installed prior to the Target Pile installation.
4. Target pile steel selection for steel used in the new NM2 target pile requires an area for staging the old NM2 target pile steel plus the additional steel required. Steel selection criteria include both geometrical considerations and minimal residual activity.
5. The coils for the E-8 magnet must be placed in the downstream end of NM2 prior to stacking the target pile steel.

9. ALIGNMENT AND STABILITY

Section 9 represents a summary of the understanding to date of the alignment and stability issues associated with the KTeV beam and spectrometer. A plan for building an alignment network for the KTeV project is presented.

Progress has been made on understanding the details associated with alignment and monitoring of each component. This is a status report on that subject. A comprehensive plan will be produced by July '94 in preparation for the installation of KTeV.

The alignment of the beam and spectrometer elements plays an important role in KTeV. Precise alignment of the neutral beam brings some of the systematic errors in the physics measurements under control. The measurement of the spectrometer location provides a primary reference for the absolute energy calibration of the CsI detector.

A substantial improvement is required in the precision of the physics measurements in this next generation of kaon experiments. The geometry of the experiment must be more precisely determined. The error contributions related to positional uncertainties of hardware must not contribute to the overall errors.

The Fermilab Survey, Alignment, and Geodesy group (SAG) has made substantial progress in upgrading their capabilities. Simulations indicate, a standard level of 3 dimensional relative measurement accuracy for any component within the KTeV internal network of ±0.25 mm at the 95% confidence level can be provided. Errors in machining, fiducialization, or adjustment are not included.

Accuracies less than 0.25 mm requires special procedures and/or technology. Work is proceeding on understanding the crucial alignment parameters of each component. There have been continuing iterations trying to balance the needs and wants of the experiment and the capabilities of the SAG group.

Alignment tolerances for individual beamline and detector components are presented in Tables 9.1.1 and 9.1.2. Shown are the installation and measurement tolerances for installation purposes, not necessarily the alignment attainable with data from the experiment. Unless specified otherwise, it should be assumed that the device needs to be stable within the measurement tolerance. All specifications and capabilities are at the 95% confidence level. It is important to note that the most stringent tolerances are only relative tolerances. The absolute (DUSAF) tolerances are of order 3 mm.

Overview

Alignment issues are driven by the physics requirements. The geometry of the CsI must be precisely known as well as its location with respect to the rest of the apparatus. The charged particle spectrometer (drift chambers and magnet) must be internally aligned since it is the basis for locating many other elements using the data. Its position relative to the CsI must be understood in order to cross-calibrate (in energy) the array. Chamber alignment is also important for proper operation of the trigger. (Ultimate understanding of the "as is" positions of the chambers will be determined from the data.)

The definition of the secondary beams depends on the alignment of the beam-target-collimator system. The axis of the beam must coincide with the axis of the spectrometer. The beam axis (see below) will be the primary reference frame for the KTeV Beam/Spectrometer system.

It is also necessary that the primary beam impinge on the target. Though the exact value of the vertical targeting angle is not critical, it must be stable. The horizontal targeting angle must be set properly in order to keep the intensities and momentum spectra of the two beams equal.

As the goals of the experiment, and the alignment issues in particular, are centered first on the neutral beam, the discussion starts there. The primary beam will be discussed after the secondary beam followed by the spectrometer. The overall methods by which the KTeV geometry will be established and implemented are addressed in Sections 9.2 and 9.3.

Stability Issues

If the locations of elements are not stable within the specified accuracy, they must be monitored and corrected. This is a serious issue, for example, with the neutral beam elements. It is for these elements that the alignment is most critical and where monitoring the alignment is a particularly challenging problem.

As in past experiments, the motion of the target or collimators, hence the beam relative to the charged spectrometer can be determined using the drift chambers. However, it is difficult to tell which component actually moved. In order to keep the level of off-line corrections palatable and to safeguard against gross movements which could endanger the calorimeter, two independent stability monitoring schemes are being studied by the KTeV beams group. The first involves using the beam itself (See Section 5.9) and the second uses a completely beam independent approach dependent on gravity and/or lines of sight (See Section 9.3.2).

The primary beam must be stable on target (see Section 1.2.). The method planned is to use an active feedback automatic beam control system (See Section 2.5). This system is similar to that developed in other external beam lines except for beam roll correction which must be developed. It will eliminate most of the problems associated with magnet fluctuations. In order for this system to work within the tolerances specified, a beam monitor must be employed which is more precise than the standard SWICs. Prototypes are currently being developed. These beam monitors must also remain stable relative to the target for the system to be effective.

The spectrometer magnet and CsI must also be kept in alignment. The distance between the downstream face of the regenerator and z-calibrator to the upstream face of the CsI array must be well known at all times. Also, temperature variations must be monitored. It is also important to know how the floor may differentially sink/rise as this will determine the motion of the spectrometer elements.

Once the geometry has been established, it is necessary to understand issues of stability and resurvey. Significant shifts in the height of various elements may occur (See Section 9.3.2). The MCenter target pile continued to sink at the rate of a fraction of a millimeter per month even some years after installation (See Figure 9.1.1). However, soil borings indicate a better bearing capacity for KTeV by almost a factor of two and a settlement Monte Carlo[58] predicts only modest motion (See Section 9.3.2)

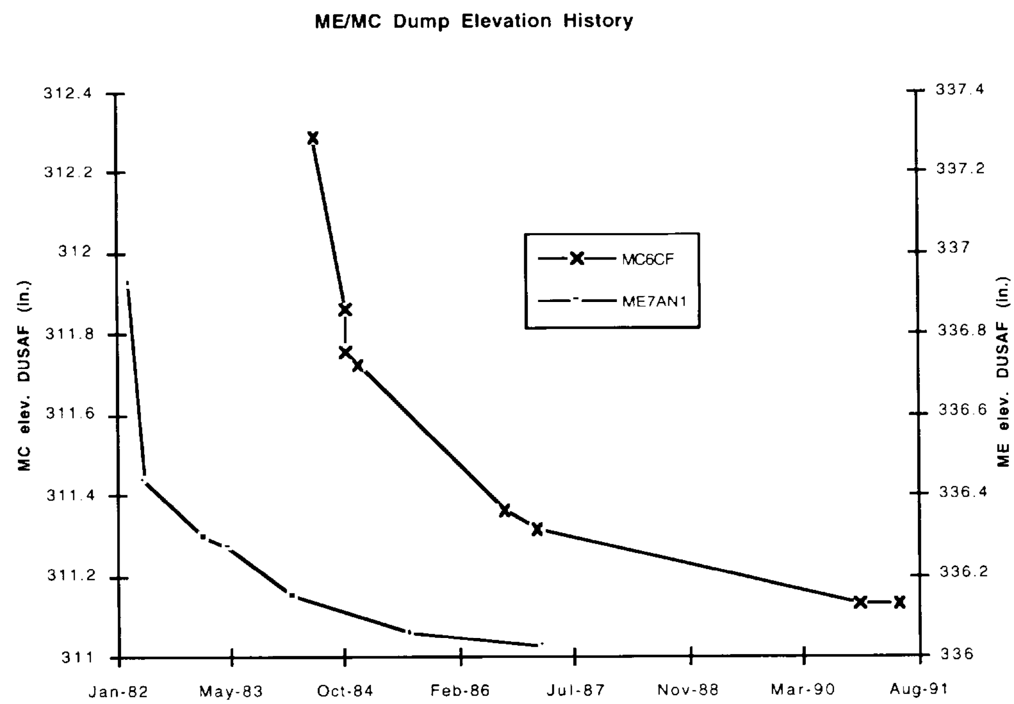

Figure 9.1.1
Elevation history of the MCenter target pile and the MEast SM12 magnet.

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[58] STS Consultants, **Geotechnical Evaluation of Proposed KTeV Project**, Northbrook, IL, 1993

9.1. Alignment and Stability Requirements

This section addresses the alignment and stability requirements of each KTeV component or subsystem . They are divided into three major subsections: the neutral beam, primary beam, and detector. The primary and secondary beam element tolerances are summarized in Table 9.1.1 and detector element tolerances in Table 9.1.2

Table 9.1.1

KTeV Beamline Alignment Requirements Summary

Item	**Description**	**Installation Tolerance**			**Measurement Tolerance***		
		x=transverse		z= beam	x=transverse	y=elevation	z= beam
		x (mm)	y (mm)	z (mm)	x (mm)	y (mm)	z (mm)
Pretarget							
ALL	All regular beamline elements	0.5	0.5	5	0.5	0.5	5
Target SWIC(s)	Target beam position monitors	0.2	0.2	5	0.2	0.2	5
Target Pile/Sec. Beam							
NM2TGT	30 cm BeO target	0.2	0.2	5	0.2	0.2	5
NM2S1	Eartly sweeper	0.6	0.6	5	0.6	0.6	5
NM2BD	Dump	0.6	0.6	5	0.6	0.6	5
NM2S2	E8 hyperon magnet - μsweep1	0.6	0.6	5	0.6	0.6	5
NM2AB1	Common absorber	0.5	0.5	5	0.5	0.5	5
NM2AB2	Moveable absorber	0.5	0.5	5	0.5	0.5	5
NM2TCOL	Primary collimator	0.2	0.2	5	0.2	0.2	5
NM2S3	Muon spoiler - μsweep2	0.6	0.6	5	0.6	0.6	5
NM2SR	Modified B2 4-4-240	0.5	0.5	5	0.5	0.5	5
NM2CV1	Slab Collimator	0.5	0.5	5	0.5	0.5	5
NM2BS	Beamstop	0.5	0.5	5	0.5	0.5	5
NM2CH	2-jaw collimator	0.5	0.5	5	0.5	0.5	5
NM2CV2	2-jaw collimator	0.5	0.5	5	0.5	0.5	5
NM2BP	beam pipe(s)	10	10	NA	2	2	NA
NM3CVH	Defining collimator	0.2	0.2	5	0.2	0.2	5
NM3S	Argonne 10-4-72	0.5	0.5	5	0.5	0.5	5
NM3BP1	18" beam pipe	3	3	NA	3	3	NA
NM3BP2	30" beam pipe	3	3	NA	3	3	NA
NM3BP3	48" beam pipe	3	3	NA	3	3	NA

* Measurement tolerances are for installation purposes only.

Alignment tolerance requirements for KTeV beamline components.

9.1.1 The Neutral Beam System

The need for precise alignment of the neutral beam derives from the requirement for a clean and well defined neutral beam. Each beam must be well contained (no halo outside the defined beam area) in order that excessive physics backgrounds not be generated. The beam must also be well contained so as not to generate excessive energy deposition in the CsI.

The secondary beam starts with the target. It must be accurately located with respect to the primary and defining collimators. Other elements in the neutral beam (sweeping magnets, dump, and so on) must be clear of the neutral beam. Additional elements of the neutral beam (for example, the various absorbers and the slab collimator) must be aligned with respect to the neutral beam in order that their function not be compromised.

Alignment and stability requirements for the neutral beam are discussed in Section 5.8.6. These requirements are based on the criteria for beam stability in Section 1.2. There are a number of contributions to the error in the position of the collimators and target:

Mechanical Tolerances
Alignment Tolerances—this includes network, measurement, and fiducialization errors.
Uncertainties in primary beam location (see below)
Long term stability

Section 5 states the alignment allocation of the error budget for the primary and defining collimators is 0.2 mm transversely.

The primary target system will consist of several individual targets. At least three targets will be used:

1 mm square 30 cm BeO
3 mm square 30 cm BeO
a short calibration/alignment target

An 'empty' target will also be available. They will be located on a remotely controlled mover which must be reproducible to less than the alignment tolerance. The target must be aligned and stable relative to the collimators and primary beam to 0.2 mm (See Section 5.3) and must be stable relative to the target beam position instrumentation to within 0.1 mm (See Section 2.5.4). It will be located inside a reentrant shielding cave allowing no direct line of sight between it and the collimators.

The common absorber will be selectable between varying lengths of Pb and Be. The motion must be very reliable so that the material covers all of both beams. The moveable absorber covers one beam only but alternates between spills. The motion must be very reproducible and reliable for about 10^6 cycles.

The primary collimator transverse alignment tolerance is 0.2 mm (see Section 5.6). It is important that there be rigid precision mechanical points attached to the collimator surface which can be measured from the aisle way. *This requirement is the same for the defining collimator. Both collimators* will be remotely adjustable in X and Y on each end.

The slab collimator will be constrained to travel in the vertical direction only with essentially two possible positions; in and out of the beam. The alignment portion of the slab collimator error budget is 0.5 mm in X and Y. The current plan is to drill 4 precision holes into each flange which will hold the fiducials.

The upstream vacuum decay region consists of vacuum pipes. These pipes must not present apertures to any parts of the detector. They are well oversized. The installation and measurement tolerances for these elements will be no more stringent than 3 mm in horizontal and vertical. The longitudinal tolerances are 5 cm for installation and 5 mm measured after installation.

The vacuum vessels after the regenerator tank will be discussed in Section 9.1.3.

Target Pile Elements

The tolerances on the target pile elements (excluding the target) are 0.6 mm. To avoid the problems of MCenter, there will be portholes into the pile for viewing the fiducials on the dump and sweeper magnet. This implies that these objects must remain rigid after they are fiducialized. In addition, there will be remote mechanical adjustment in the vertical plane. The portholes will be plugged when not being used. The apertures in the horizontal plane on the Eartly sweeper and on the beam dump will be ±6.35 mm larger than necessary so that no horizontal adjustment will be needed after initial installation. The vertical apertures also have a clearance ±6.35 mm except for the bottom surface of the dump which is only 2.54 mm. Therefore, these items do not have to be stable to the measurement tolerances in Table 9.1.1.

Both NM2S2 and NM2S3 have transverse installation and measurement requirements of 0.6 mm. They will have the capability of horizontal and vertical adjustments. The current plan is to use shims, jacks, and rollers. The stability allowance is ±6.35 mm .

9.1.2 The Primary Beam

The primary beam is initially defined in Switchyard. The beam is transported to the KTeV primary target through the elements as detailed in Section 2. The beam is brought onto the production target with a downward vertical targeting angle and a zero horizontal targeting angle. The vertical targeting angle is variable using the AVB (Angle Varying Bend) system. Only small adjustments are possible in the horizontal using the trim system.

The tolerance to which the primary and secondary beams must be aligned in the horizontal plane is determined by the requirement that the intensity of the two neutral beams be equal to 1 % and that the momentum spectra be equal to 0.1% (See Section 5.3). The primary and secondary beams be aligned and stable to $Dq_x = Dq_y = 20\ \mu$rad. This assumes a small (1 mm) target; and a beam size less than the target size. This is an issue particularly with respect to E832.

<u>Primary Beam Element Tolerances</u>

The primary beam elements are installed to the standard beam line tolerances of 0.5 mm in the horizontal and vertical. The only element(s) with special requirements is the targeting beam *instrumentation* (See Section 2.5.4). These will be used to control the beam position and angle on target and must be stable relative to the target within 0.1 mm. This requirement along with the target tolerances poses constraints on the engineering design in this area. It should also be noted that the Case 3 scenario (See Section 2.5.6) which mentions instrumentation stable to 250 µm at a distance of 1200' has not yet been addressed.

9.1.3 Detector Element Tolerances

Here we discuss installation and measurement tolerances for each of the detector elements starting from upstream. This section is summarized in Table 9.1.2. The detector is assumed to start with the Mask-Anti.

Two spectrometer issues are central to alignment considerations. The first is that of aligning the charged particle spectrometer. The chambers must be well aligned with respect to one another and to the magnet. This assures proper operation of the trigger and cross-calibration of the CsI Calorimeter. Second, the locations in Z of the CsI, downstream face of the regenerator, the Z-Calibrator and the charged particle spectrometer play a fundamental role in setting the absolute energy calibration of the CsI calorimeter.

Table 9.1.2

KTeV Detector Alignment Requirements Summary							
Item	**Description**	**Installation Tolerance**			**Measurement Tolerance***		
		x=transverse		z= beam	x=transverse	y=elevation	z= beam
		x (mm)	y (mm)	z (mm)	x (mm)	y (mm)	z (mm)
Experiment							
NM4MASK	Mask-anti	1	1	5	1	1	0.5
NM4REG	Active regenerator	1	1	5	1	1	1
NM4TANKR/6	Vacuum decay tank	NA	NA	NA	NA	NA	NA
NM4RC6	Ring veto counter- vacuum	3	3	NA	0.5	0.5	1
NM4TANK6/7	Vacuum decay tank	NA	NA	NA	NA	NA	NA
NM4RC7	Ring veto counter- vacuum	3	3	NA	0.5	0.5	1
NM4TANK7/8	Vacuum decay tank	NA	NA	NA	NA	NA	NA
NM4RC8	Ring veto counter- vacuum	3	3	NA	0.5	0.5	1
NM4ZCAL	Z-calibrator (Pb glass in vacuum)	10	10	NA	1	1	1
NM4TANK8/9	Vacuum decay tank	NA	NA	NA	NA	NA	NA
NM4RC9	Ring veto counter- vacuum	3	3	NA	0.5	0.5	1
NM4TANK9/10	Vacuum decay tank	NA	NA	NA	NA	NA	NA
NM4RC10	Ring veto counter- vacuum	3	3	NA	0.5	0.5	1
NM4TANK10/W	Vacuum decay tank	NA	NA	NA	NA	NA	NA
NM4WIND	Sailcloth vacuum window	1	1	NA	0.5	0.5	0.5
NM4SHIELD	Thin Vac. window shield	NA	NA	NA	NA	NA	NA
NM4DC1	Drift chamber	0.25	0.25	0.5	0.25	0.25	0.25
NM4HE1	Helium Bag	NA	NA	NA	NA	NA	NA
NM4SA2	Spectrometer veto counter	3	3	5	0.5	0.5	1
NM4DC2	Drift chamber	0.25	0.25	0.5	0.25	0.25	0.25
NM4HE2	Helium Bag	NA	NA	NA	NA	NA	NA
NM4AN	Spectrometer magnet	0.5	0.5	1	0.25	0.25	0.25
NM4SA3	Spectrometer veto counter	3	3	5	0.5	0.5	1
NM4DC3	Drift chamber	0.25	0.25	0.5	0.25	0.25	0.25
NM4HE3	Helium Bag	NA	NA	NA	NA	NA	NA
NM4SA4	Spectrometer veto counter	3	3	5	0.5	0.5	1
NM4DC4	Drift chamber	0.25	0.25	0.5	0.25	0.25	0.25
NM4TRD1-8	Wire chambers	1	1	5	0.5	0.5	5
NM4HODO	Trigger hodoscopes (H & V)	1	1	5	1	1	3
NM4CIA	Spectrometer veto - CsI anti	1	1	2	0.5	0.5	1
NM4CA	Collar-anti#	0.1	0.1	NA	0.1	0.1	NA
NM4EMCAL	CsI Calorimeter	1	1	5	1	1	1
NM4MU0	Cosmic ray calibration telescope	NA	NA	NA	NA	NA	NA
NM4PB	Lead wall%	5	5	5	NA	NA	NA
NM4MU1	Muon counter/hadron veto	1	1	5	1	1	3
NM4FE	Muon filter%	NA	NA	10	NA	NA	NA
NM4BTRD	Beam TRD	1	1	5	1	1	5
NM4BA	Back-anti, beam veto	2	2	5	1	1	3
NM4BD1	Neutral hadron dump/muon filter	NA	NA	10	NA	NA	NA
NM4MU2	Muon veto	1	1	5	1	1	3
NM4BD2	Neutral hadron dump/muon filter	NA	NA	10	NA	NA	NA
NM4MU3	Muon veto	1	1	5	1	1	3

* Measurement tolerances are for installation purposes only.
# Tolerances will be achieved through precision machining not using a survey crew (see text)
% Beam hole edges must be measured to 2 mm for the Pbwall & 1 mm for the muon filter

Alignment tolerance requirements for KTeV detector components.

Mask Anti (E832 only)

The Mask Anti defines the start of the decay region for the K_L beam. In E731[59], the acceptance was largely governed by several limiting apertures. Those defined by the Active Mask and the Collar Anti were the most sensitive. A 650 μm error in the measurement of the size of the mask would bias e'/e by -0.5×10^{-4}. The size and location was ultimately understood with an uncertainty of 70 μm ($|\Delta \mathrm{Re}(e'/e)| = 0.02 \times 10^{-4}$) using Ke3's in the off-line analysis. This was driven by the systematic uncertainty in track projection from the drift chambers.

The KTeV drift chambers are the same ones used in E731 with improved electronics and wires. The resolution will be equal to or better than before. Therefore, the final, most precise understanding of both the size and the transverse position of the Mask Anti will be done using Ke3's found in the data. The installation tolerance is 1 mm in X and Y.

The tolerance for the Z installation is 5 mm but should be known to 0.5 mm with respect to the regenerator. The z distance between the Mask Anti and the regenerator can be measured prior to installation. The current engineering specification is that the distance cannot change by more than 0.5 mm. If that method proves impractical, a fiducial must be brought out of the vacuum so that it can be measured using one of the methods for z-calibration proposed in Section 9.3.2. This will be decided after additional engineering input is obtained from the FNAL Mechanical Support Dept.

The edges of the beam hole in each lead plate must vary by less than 100 μm.[60] The measurement of the plate to plate variation after assembly will tentatively be done by UCLA using a special measurement jig which has not yet been designed. However, should this proposal prove impractical, the measurement must be made by a survey crew. Similar measurements using standard alignment techniques done on RC7 resulted in an error of s @ 250

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59 L.K. Gibbons et al, **A Precise Measurement of the CP-Violation Parameter Re(e'/e) and Other Kaon Decay Parameters**, 1993, pp. 305-309.
60 J. Jennings, **Mask Anti Conceptual Design**, KTeV Collab. Meeting, 1994

μm. Therefore another method may need to be developed in order to meet this specification.

Regenerator (E832 only)

The regenerator is an important element in E832. It is housed entirely under vacuum. It is essential that it covers one of the two beams entirely without encroaching onto the other beam. The regenerator must also change beams every spill. The installation and measurement tolerances are 1 mm in both horizontal and vertical.

The downstream face of the regenerator determines the start of the decay region for the K_S beam. It is also a calibration point for the determination of the absolute energy scale. The position of the downstream face of the regenerator must be known to 1 mm with respect to the front face of the CsI array. The regenerator must move so that the front face remains in a plane parallel to the CsI array and which is also perpendicular to the beam line.

The tolerances in z measurement of the CsI, Regenerator, and Z-Calibrator are important, as an error here contributes directly to the error in e'/e. A z error of 1 mm will contribute minimally to the total final error. Note that the ±4 °F temperature tolerance for the experimental hall leads to worst case changes in the distance between the regenerator and CsI due to floor expansion of about 3.2 mm, which is larger than the 1 mm tolerance. There is a proposal to monitor this distance using an EDM (Electronic Distance Meter). See Section 9.3.2.

In order to measure the position of the regenerator, there will be viewing ports in the regenerator vessel. It will be possible to measure the position of the front face of the regenerator as a function of its position using conventional survey techniques. The plane of the front face of the regenerator will be referenced along a line that can then be referenced to the CsI array.

Other methods are being considered for monitoring the position of the regenerator with respect to fiducials outside the regenerator tank.

Vacuum Vetoes

The alignment requirements of the Vacuum Vetoes are discussed in the Vacuum/Veto design report[61]. The vetoes must be installed to an accuracy of ±3 mm in X and Y (and rotation). They should be measured after installation to 0.5 mm. The Ring Counters are not in general defining apertures for $K \rightarrow 2\pi$ decays in E832, though they may be for some of the E799-II modes. The absolute z location of the regenerator and its associated vessel will be chosen, and the location of the vetoes will be fixed by construction of the vacuum vessels. The z locations should then be measured to 1 mm.

The ring veto counters have each been provided with tooling balls. The internal geometry of the counters will be referenced to the external tooling balls and then alignment will be relative to those tooling balls. RC7 has been measured in detail. The inside edges are defined and understood to 0.25 mm.

Z-Calibrator

The design of the Z-Calibrator is in progress. It flips up into the beam for special runs. There will be viewing windows for alignment access. The purpose is to provide a z reference point to confirm the understanding of the z scale in the neutral mode analysis. The horizontal and vertical position is not critical (to 10 mm) as it is larger than the area it is required to cover. It must however be installed very accurately perpendicular to the beam—to 0.5 mrad. The z location of the Z-Calibrator must then be determined relative to the front face of the CsI (and of course the regenerator) to 1 mm. Monitoring this position is discussed in Section 9.3

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[61] D. Jensen et al, **Vacuum Veto Design Report**, 1993

Spectrometer Magnet

In discussing the spectrometer magnet, it must be noted that assumptions regarding survey accuracy and a number of other considerations have gone into the design specification for the magnet. Assumed in the design of the magnet was that it would be possible to determine the relationship between a track and the field to 1.0 mm. This is the total error budget allowed in the process of locating the field measuring equipment relative to the magnet, and then locating the chambers relative to those same fiducials. Also included in the error budget are errors associated with the magnet measuring facility[62]. The contribution to this error budget from the survey location of chambers relative to the magnet is 0.25 mm.

The installation of the magnet is to conventional tolerances. It is required that the pole pieces be in a horizontal plane. The location of the magnet must then be surveyed so that its position relative to the chambers is known to 0.25 mm transversely and 0.25 mm in longitudinal position.

The magnet will be extensively fiducialized. Seats for laser tracker corner reflectors will be epoxied to four places on each of the coils, as well as to the sides of the yoke of the magnet. The temperature of the yoke will also be monitored in order to develop predictors for motion that might be detected.

Drift Chambers

Due to their excellent resolution and efficiency, the drift chambers are the cornerstone by which most of the positional and stability information of the experiment is understood. Ultimately, the drift chamber locations must be known to a fraction of the resolution, which is approximately 80 microns. Figure 9.1.2 shows the level of motion experienced in E731[63]. Apparent motion of the target is amplified because of the long lever arm from the first

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[62] D. Jensen et al, **Spectrometer Magnet Design Report**, 1993

[63] L.K. Gibbons et al, **A Precise Measurement of the CP-Violation Parameter Re(e'/e) and Other Kaon Decay Parameters**, 1993, p. 84.

chamber to the target. A 1 mm shift in the target position corresponds to only a 0.12 mm shift in the first chamber.

Special muon calibration runs are used to determine Δx, Δy, and Δq *relative* to one another. This method had a reproducibility of about 5 μm for offsets and ~10 μrad in roll in E731[64]. Two-track events were used to determine the corkscrew rotations. Once the relative positions are determined, the chambers can be treated as a rigid body and the locations of other elements in the spectrometer relative to the drift chamber magnet system can be determined using track reconstruction.

The location of the target relative to the drift chamber system will be determined using $\Lambda \rightarrow p\pi$ events. The high momentum protons reduce the multiple scattering contributions to the error in finding the target location. This gave a single event sensitivity of 3 mm in E731[65], so 50k to 100k Λ decays should give us ample statistics to be in the 10 μm range. This is better than can be done with a survey crew.

While the alignment group cannot measure transverse and roll as well as can be done with the beam, there are certain quantities to which the chambers are insensitive. Z positions need to be measured as well as possible. In MCenter, this measurement suffered from systematic problems. The z-measurement tolerance is currently 0.25 mm. However, it should be noted that the floor could expand/contract as much as 1 mm over the 20 m span of the drift chamber system with a building tolerance of ±4°F. This needs further study. Pitch and yaw cannot be measured directly, so it is important that the chambers be initially aligned to within 0.2 mrad of perpendicular[66]. Non-orthogonalities in the drift chamber wires can cause difficulty in measuring rotations. This must be measured during fiducialization with a tolerance of 0.15 mrad.

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64 Ibid. pp. 74-76.

65 L.K. Gibbons et al, **A Precise Measurement of the CP-Violation Parameter Re(e'/e) and Other Kaon Decay Parameters**, 1993, p. 81.

66 S. Somalwar, Private communication, 1993

Even though the transverse positions of the chambers will be determined with the beam, they should be aligned and measured to a tolerance of 0.25 mm with respect to the beam and spectrometer magnet. This will keep the level of corrections to a minimum and satisfy the geometry requirements of the trigger.

Laser Tracker sphere mounts (4) will be mounted to each chamber. Before installation, the locations of the sense wires will be determined relative to the corner reflector locations. There will be some redundancy in order to be able to fully align the chambers and readily resurvey them.

Hodoscopes

The hodoscopes are to be installed conventionally. The installation accuracy is 1 mm. The counters should be set horizontally or vertically to that same 1 mm over their full lengths. The z location is not critical. The final z location should be measured to 3 mm. The final understanding of the positions of the hodoscopes will be determined from the data. The edges of the holes in the trigger hodoscopes must be known to 0.25 mm, but will be measured using tracks[67]. The locations of the holes should be located to ±1 mm so that there is no chance of beam scraping on the inner edge of the holes.

Spectrometer and CsI Antis (SA's, CIA)

The same criteria applied to the RC counters apply to the SA's. The installation tolerances are the same. Measurement of the locations of these veto counters is important as it is difficult to study the counters with reconstructed tracks. Since three of the drift chambers are currently planned to be mounted on the SA stands, their overall stability needs to be the same as the drift chambers. Their z positions should be known to 1mm.

There is still some discussion within KTeV as to how well the CIA needs to be known. It is believed to not be a limiting aperture in E832. In

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67 G. Thomson, Private Communication

E731[68], mismeasurement of the size and location of outer apertures such as this contributed little to the error of e'/e because it is located on the outer edge where the illumination is low. The tightest number being considered for E832 is 100 μm (aperture with respect to the CsI array), which can be studied using reconstructed tracks.

It is important that the CIA be installed and measured accurately. It should be installed to 1 mm transversely and measured to at least 0.5 mm.

<u>Cesium Iodide Array</u>

Several measurements must be made on the CsI array. However, measuring the array with a survey crew will be difficult since it is located in a hermetically sealed house in tight quarters. The current plan is to measure as much as possible using other means such as large micrometer calipers. As the position resolution of reconstructed clusters will be 1 mm, the crystal locations must be known to a small fraction of a millimeter. A precision measurement at this level would require a line of sight from experimental hall network monuments to the laser tracker then to at least three fiducials on the array using the same setup. Accomplishing this would consume precious space in the blockhouse and require additional resources and time during installation when other solutions exist. The current solutions hinge on four major assumptions:

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68 L.K. Gibbons et al, **A Precise Measurement of the CP-Violation Parameter Re(e'/e) and Other Kaon Decay Parameters**, 1993, pp. 305-309.

1. Precise knowledge of the transverse locations of the crystals, Collar Anti, and CIA locations can be determined by the data.
2. Stacking can be done without the aid of a survey crew.
3. The supporting plates for the array will remain rigid, with deflections less than 125 μm.
4. The Collar-Anti will be positioned through precision machining of its reference surfaces and the cans onto which it is placed.

The precise transverse location of the array will be determined using Ke3's found in the data[69]. E731[70] had enough statistics to determine mean positions to 10 μm and rotation to a systematic uncertainty of 50 μrad. A minimum of one Ke3 per block per spill will be written to tape during regular E832 data taking[71]. Special runs will be made periodically if this illumination is insufficient.

The position of the individual crystals must be measured relative to each other and to the reference plates at stacking time. The current plan is that KTeV will measure these without a survey crew by using special large calipers. This method has not yet been field tested to confirm its feasibility, but needs to be very soon. The design of the blockhouse extension would need to be modified to accommodate a survey crew.

The requirements for the alignment group have been reduced to two sets of measurements with looser tolerances than before; but they are still very important. The first is setting the stand in place and measuring the perpendicularity of the horizontal and vertical reference plates. The blockhouse walls will not have been installed at this point, hence allowing access room. The second set of measurements is determining the three dimensional position of the array with respect to the rest of the spectrometer during the final alignment. Since precise measurement will be done with the data, the tolerance for this process has been loosened to 1 mm. This is driven by keeping any beam halo from hitting the pipe blocks. At the 1 mm level, a

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69 R. Ray, **Survey Issues for the CsI Array**, 1994
70 L.K. Gibbons et al, A Precise Measurement of the CP-Violation Parameter Re(e'/e) and Other Kaon Decay Parameters, 1993, pp. 80-81.
71 E. Cheu, Private Communication, 1994

survey crew can align the calorimeter using conventional optical techniques. The fiducials on the array reference plates will be accessed through 4" portholes adjacent to each tooling ball. The portholes will remain plugged except during the actual reading which will take minutes to perform. This is not long enough to degrade the atmosphere inside the blockhouse due to the positive pressure[72].

Since the absolute energy scale is set by the distance from the downstream face of the regenerator and from the Z-calibrator to the front face of the CsI, this will be a crucial measurement. The tolerance for this distance has been set to 1 mm. The pitch, yaw, and flatness of the CsI array itself should be less than this so as to not dominate this error. The initial z measurement will be made with a survey crew. Another means must be developed to monitor this parameter. The data is very insensitive to it. The current proposal is to use an EDM (Electronic Distance Meter) to measure the location of extensions from the support under the CsI array. This will make it possible to monitor the Z and the yaw. See Section 9.3 for more details. Roll and pitch will be monitored with electronic levels accurate to about 50 μrad.

Collar Anti

The Collar-Anti (CA) is located inside the CsI blockhouse. As with the Mask Anti, it is a limiting aperture for E832. In E731[73], a mismeasurement in size of the CA had a noticeable effect (in terms of the E832 error budget) on the observed ratio of K_L/K_S in the neutral mode (-0.021% for a 70 μm error). Its position was not as sensitive, but the experiment was able to determine its size and location with a systematic uncertainty of 15 μm.

For KTeV, the CA must be aligned to 100 μm[74] in horizontal and vertical with respect to the precision holes with which the beams pass through the CsI calorimeter. Ultimately, the size and position will be verified

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72 R. Ray, Private Communication, 1994

73 L.K. Gibbons et al, A Precise Measurement of the CP-Violation Parameter Re(e'/e) and Other Kaon Decay Parameters, 1993, pp. 305-309.

74 T. Yamanaka, Private Communication, 1994

with data, but it is necessary to have an independent measurement given its importance. Due to space constraints, it will be difficult to align this device using standard survey techniques. However, since the Collar Anti will be mounted directly to the supports where the beam passes through the CsI, one can "capture" it through precision machining and the use of shims if necessary. It's small size allows for direct measurements with a micrometer. Since the temperature inside the CsI house is strictly controlled and the CA is so small, there will be negligible size changes as a result of temperature effects (<3 μm/°C).

Particle ID (TRD's, muon system, BA)

The first section of the particle ID part of the detector consists of the Transition Radiation Detectors (TRD's). They must be installed to a survey tolerance of 1 mm and measured to 0.5 mm transversely[75]. They will be resurveyed relative to the drift chambers using tracks. They must be installed perpendicular to the beam within 1 mrad.

The muon system consists of shielding and scintillation counters. The shielding is 6" oversize so transverse position is not critical, but it should be perpendicular so there is a z tolerance of 1 cm for each corner. However, the beam hole edges in the first muon filter (Pb Wall) should be measured to 1 mm (2 mm)[76]. The counters should be installed and measured to 1 mm transversely.

The back anti must be installed to 2 mm[77]. Its position is not critical as it is not used as a part of the detector. It is rather a veto that is larger than the neutral beam (as it must contain the showers).

The beam TRD is not used for position information, and hence only needs to be positioned within 1 mm.

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75 Y.B. Hsiung, Private Communication, 1994
76 Ibid.
77 Ibid.

9.2. Methodology

This section addresses the procedures necessary for the installation and positional maintenance of the KTeV components to the specified tolerances. The Fermilab Survey-Alignment-Geodesy Group (SAG) has considered three needed categories:

1. External survey control network.
2. High accuracy internal survey control network.
3. Maintenance of the internal network and monitoring of relative component positioning.

When measurement errors are specified by the SAG group, the errors refer to the 95% confidence level errors. In the analyses below, these errors were calculated in three dimensions and then projected onto the horizontal and vertical planes. The 95% errors quoted correspond to 2.4 standard deviations in two dimensions.

There are two methods that may be considered for establishing the KTeV coordinate system. The first method consists of extrapolating the proton beam line on through the KTeV neutral beam line and thence to the spectrometer. This is a point-azimuth technique. Using this method, a simple extrapolation through the KTeV system at, for example, laser tracker resolution suggests that the errors in transverse location would be of order one millimeter. This is unacceptably large. A more careful preanalysis by the SAG group suggests that the errors by this technique would in fact be several millimeters.

The other method, discussed below, is based on a rectangular grid of monuments outside the KTeV halls tied to the KTeV system through sight risers. A preanalysis based on this method shows that it is several times more accurate. The detailed analysis by the SAG group suggests that this system is capable of sustaining a grid with accuracy of order 0.2 mm for the basic reference system. This level of accuracy can probably be improved to 0.1 mm or better for relative surveys in the KTeV neutral beam system. This would provide an adequate reference system for KTeV. The final alignment accuracy of various elements of the neutral beam and spectrometer has a rigorous lower bound set by the references themselves!

9.2.1 External Survey Control Network

The External Survey Control Network will consist of eight or more survey monuments. To ensure a strong geometric figure, these monuments will be placed as near to the project site as construction will allow. This network will be tied to the current DUSAF site coordinate system using both conventional and Global Positioning System (GPS) techniques, yielding positional accuracies of ±3 mm relative to that site system. Initially, this network will be used by the construction contractor for a layout reference system and for quality control checks of the layout work by the SAG Group.

Internal to itself, this network will achieve relative positional accuracies of ±0.2 mm. This network will also be used to transfer the current DUSAF site coordinate system into the internal control network. This transfer will necessitate a high precision survey of the exterior network at the time the transfer is made.

9.2.2 High Accuracy Internal Control Network.

The High Accuracy Internal Network will make it possible to establish relative component positioning to ± 0.1 mm. It will also be the basis for a dynamic monitoring system for relative position checks on components. To achieve this, the internal network must be an independent survey, using the transferred points for constraint purposes. It will of course be necessary to reestablish the reference system from time to time because of the motion of the building and internal monuments (see Section 9.2.4).

Good control (reference) points are required for a strong network. These are points which represent constraints on azimuth and coordinates. Section 9.2.3 addresses the optimization of the number and location of these points.

The configuration of the network is limited by the shape and the geometry of the enclosures and the experimental hall. This dictates that the KTeV internal network be a longitudinal network. The preanalyses conducted on the two basic survey framework systems is based on two chains of braced quadrilaterals: seven in the NM2 enclosure and nine in the experimental hall. A braced quadrilateral has diagonal measurements to the corners. This primary underground control network will consist of 36 monuments, the positions of which must satisfy a number of criteria:

- the points must be easily accessible
- the density of the points has to be great enough to cover the objects to be surveyed
- the network structure must be flexible enough for any future needs

To improve the isotropy of the network and compensate the weaknesses caused by the poor ratio between the length and width of braced quadrilaterals, additional diagonal measurements spanning adjacent quadrilaterals will be made. Redundant observations will be performed to ensure quality and uniformity of accuracy.

The points of this primary control network will be fixed and used as the basis of a denser secondary network for component alignment. This densification network will be developed using primarily the Laser Tracking Interferometer. These points will be placed strategically to minimize the number of observations necessary for component positioning, also allowing for eventual smoothing routines, while providing monuments close to the beam line for optical tooling setups if practical.

The underground reference control system is represented by monuments permanently imbedded in the enclosure floor and monuments rigidly attached to wall brackets. The actual monuments are represented by high-precision socket type holders to support spherical reflectors whose centers define the monument coordinates in all three dimensions.

All the coordinates of the underground network will be computed utilizing three dimensional rigorous least square adjustments. Error propagation analysis indicates that this network should determine absolute tunnel monument positions to better than ±0.2 mm (±0.4 mm) and relative component positions to generally better than ±0.1 mm (±0.2 mm) for the case of six (four) sight risers.

A horizontal sight pipe is necessary for direct visibilty in between enclosures. This considerably increases the relative accuracy between critical components in NM2 and NM3,4 such as the collimators. The absence of this in MCenter caused severe problems with measurements between enclosures.

9.2.3 Network Preanalysis

In order to develop a plan for the number of monuments and sight risers, and to understand quantitatively the tradeoffs of various options, a network simulation and preanalysis was performed. In fact, two independent analyses were performed, using somewhat different methods, but leading to the same general results. In these analyses, various numbers of reference points were modeled. The reference points are well defined by sight risers tied to outside monuments and their relative error is assumed to be zero. The KTeV coordinate system is then built starting with and constrained by these reference points.

The minimal set of reference points is two. As many as 6 reference points were assumed. For each case the error ellipses in longitudinal and transverse directions were determined. The error ellipses correspond to the 95% confidence levels for the accuracy of that network. Results of these analyses are presented in Figures 9.2.1 and 9.2.2. The major axis corresponds with the horizontal plane and minor axis with the longitudinal. As can be seen in Figure 9.2.2, the longitudinal error is already well behaved in the case of two sight risers. However, the transverse error in Figure 9.2.1 is unacceptably large with only two sight risers. The errors with a larger number of constrained points (sight risers) are much more in line with the KTeV requirements. It is apparent that 4 sight risers is the minimum number necessary for KTeV, i.e. at least two more are needed over what is specified in the current civil construction package.

In the vertical plane, gravity provides additional constraints just as sight risers do in the horizontal. Using spirit levels alone, relative elevations between any two points in a controlled environment can be determined within 0.25 mm at the 95% confidence level.

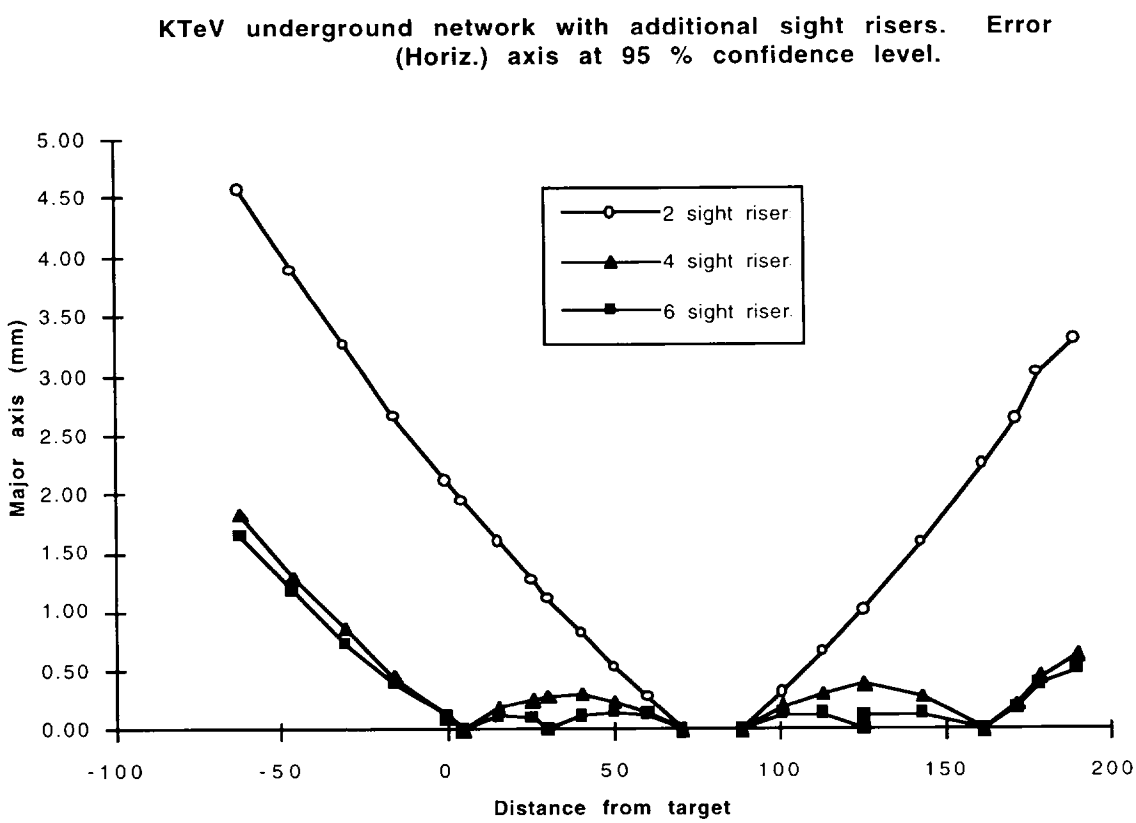

Figure 9.2.1
Results of pre-analysis showing the transverse error propagation at the 95% confidence level as a function of z for the current 2 sight riser configuration and for additional sight risers.

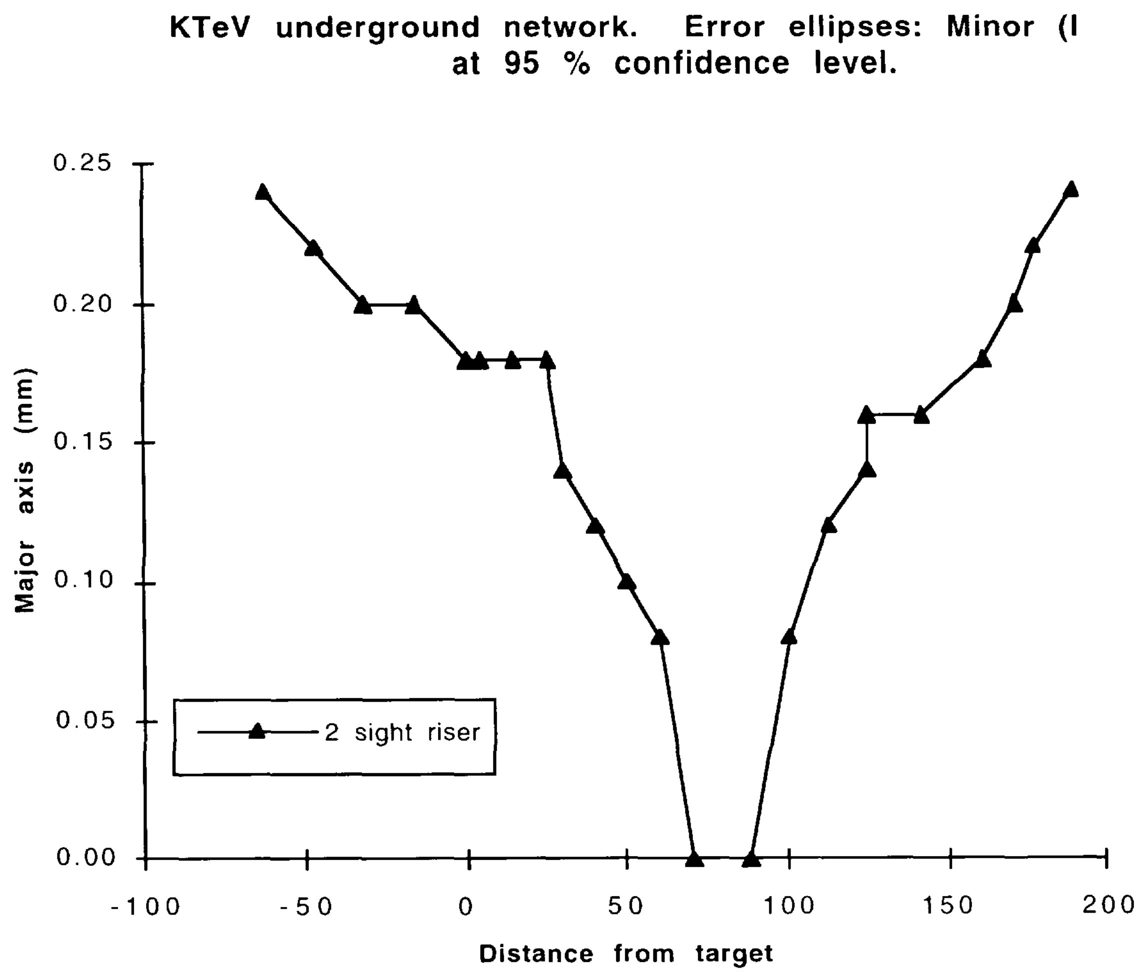

Figure 9.2.2
Results of pre-analysis showing longitudinal error propagation at the 95% confidence level as a function of z for the current 2 sight riser configuration.

9.2.4 Maintenance of the Internal Network and Monitoring of Relative Component Positioning.

Maintenance of the internal network and monitoring of relative component positioning will be required since all the survey and alignment tasks analyzed pertain to a static situation. The positional accuracies of the internal network and the component positioning are only valid during the time it takes to complete the survey (See Section 9.3.2 discussion on stability). The standard way to reposition critical components is with a survey crew.

Depending on the circumstances, this may take from several hours to several days because the network will also need to be resurveyed. To monitor this movement, a dynamic monitoring system may be employed. The sophistication of this monitoring system depends on two factors:

1. The specified accuracies needed for relative positioning of critical elements.
2. The stability of the internal survey monuments established at or near the critical elements.

9.3. Implementation

Having established the alignment and survey methodology, an implementation procedure must be developed. There are four elements needed to implement the KTeV alignment plan:

1. Interface with the civil construction group to provide necessary specifications and assistance before and during facility construction.
2. Develop general and specific fiducialization and alignment procedures for beam and detector elements.
3. Give specifications for alignment hardware.
4. Provide for an on-line stability monitoring system which supplies information independently of beam and detector data.

9.3.1 KTeV Civil Construction Issues

An array of monuments is installed in undisturbed soil in the area of the construction. These monuments will be used to monitor the civil construction. Many of them will be reused for the external network.

Figure 9.3.1 shows the design of the sight risers and underground monuments discussed in Sections 9.2 and 9.3.2 respectively. Figure 9.3.2 is a cross section drawing of the end of NM2 showing the location of the horizontal sight pipe used to bring survey control directly between enclosures.

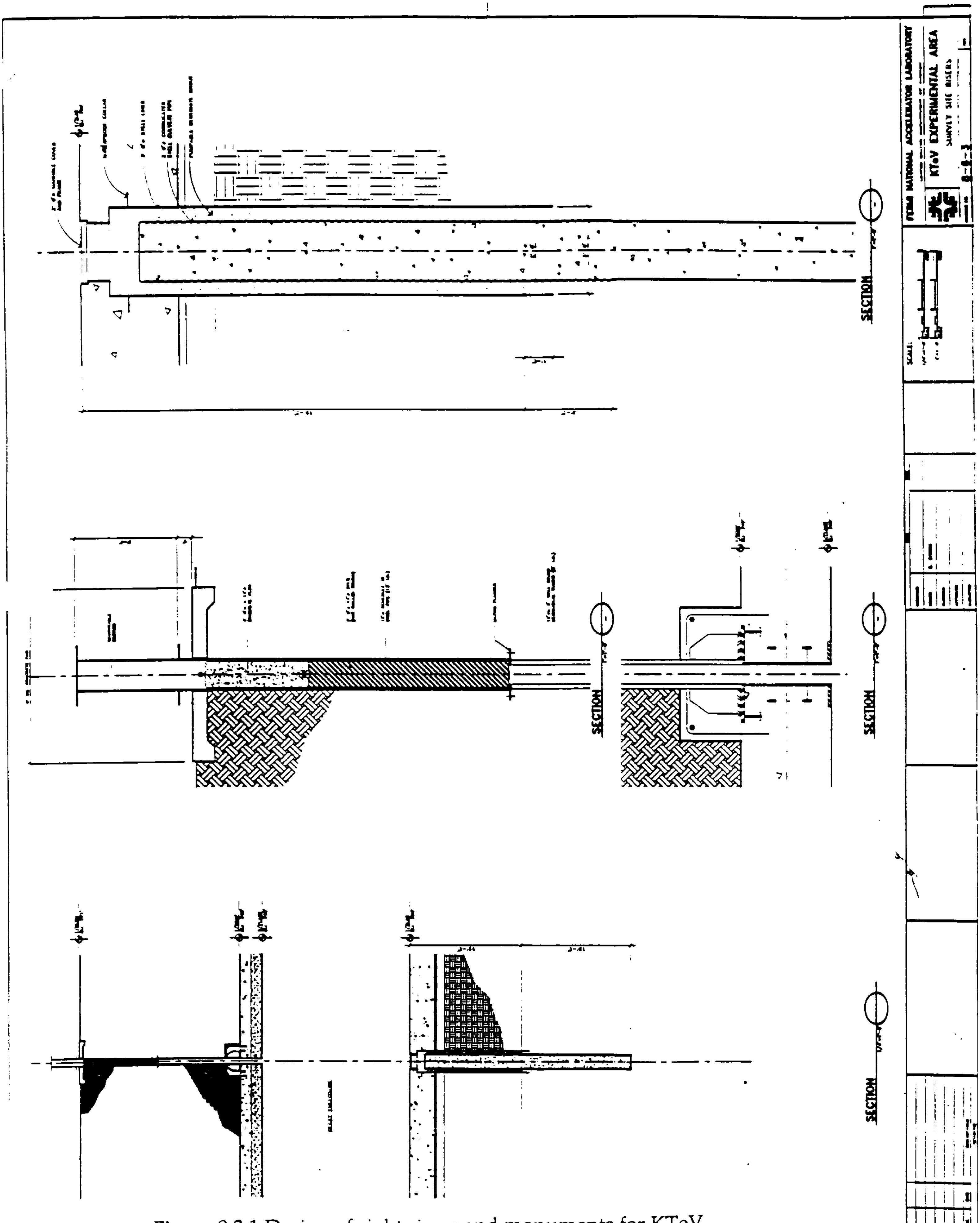

Figure 9.3.1 Design of sight risers and monuments for KTeV.

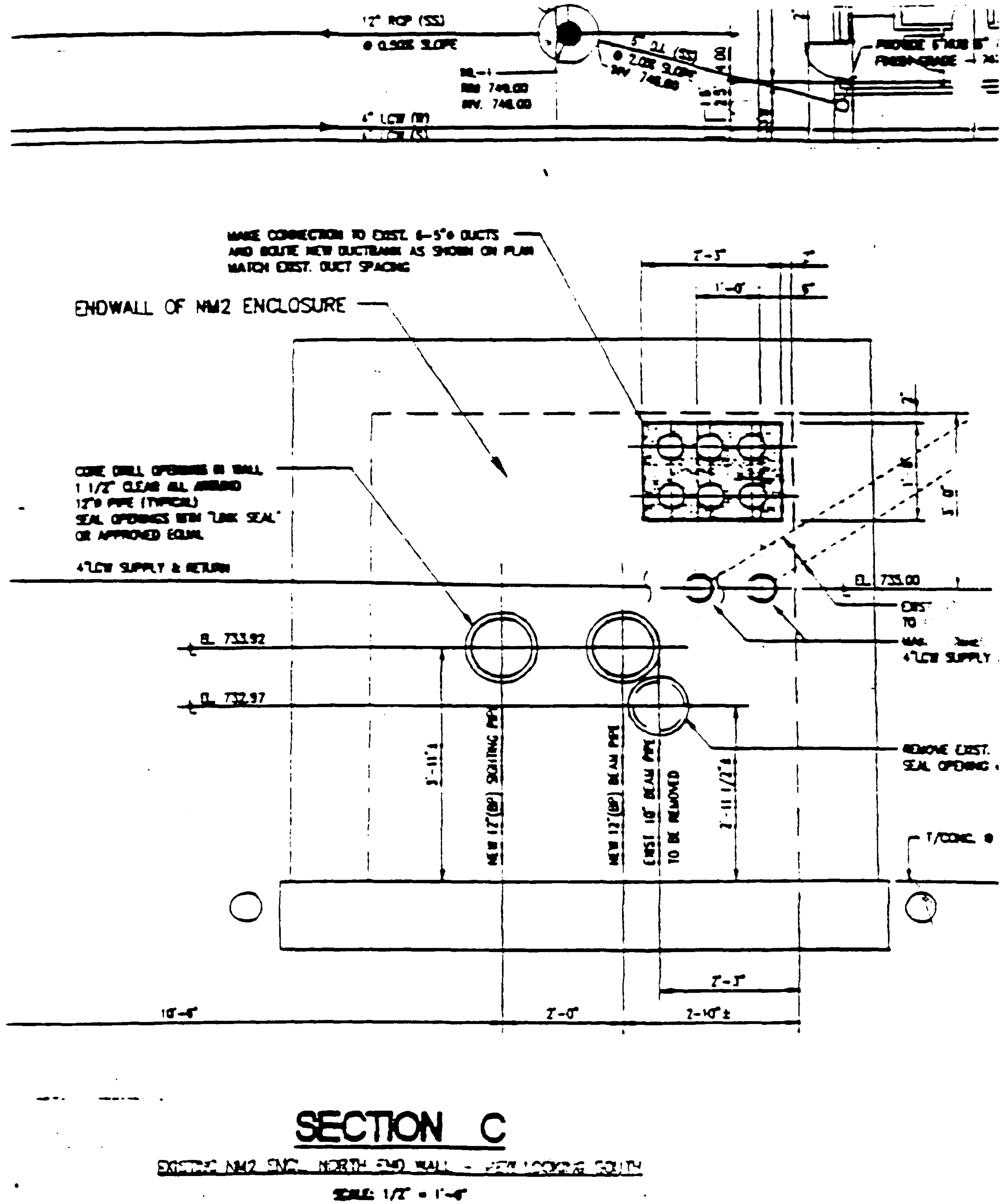

Figure 9.3.2 Cross section drawing of the end of NM2 looking upstream showing the location of the horizontal sight pipe.

After the KTeV civil construction is completed, the SAG group requires two weeks of sole occupancy of the experimental hall to establish the internal control network. The experimental hall needs to be free of obstructions at that time.

9.3.2 Stability

There are several factors which can upset the stability of internal floor monuments in an experimental hall in the 0.1 mm to 0.2 mm range. Among these are new construction, floor loading, temperature, weather, poor construction, etc. Measurements taken at other labs[78,79] provide evidence that these can be significant problems.

Data has been taken to study the stability of the existing NM2 enclosure. Over a period of 2 months, the dump area in NM2 is believed to have shifted vertically 0.5 mm in relationship to the rest of the enclosure. This number has an error bar of about ±50%. NM2 is an existing enclosure so it should not be suffering from the large settling effects often encountered in new construction. Since this is a short term study of only a couple months, it is not known whether this is a trend or an oscillation. However, it confirms that there is a need for stability monitoring of some kind.

Monitoring of relative horizontal motion in the NM2 hall has also been done using a set of optical instruments. This data is still being analyzed.

A soil contractor, STS, has attempted to predict the KTeV experimental hall settlement using a Monte Carlo called Settl/G[80]. Based on a series of soil borings, predictions have been made for initial (6 months) settling of the KTeV hall as well as long term (5 years). Figure 9.3.3 shows the location of

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[78] **Proceedings of the First International Workshop on Accelerator Alignment,** pps, 4-24, SLAC, Stanford, 1990

[79] **Proceedings of the Third International Workshop on Accelerator Alignment,** CERN, Geneva, 1993

[80] STS Consultants, **Geotechnical Evaluation of Proposed KTeV Project**, Northbrook, IL, 1993

the points which were calculated and Figure 9.3.4 shows the predicted settlement of those points at floor level and for two soil layers below floor level. The second soil layer ends at bedrock which is assumed stable. The numbers imply that settlement will be quite modest after initial installation and that soil layers closer to bedrock have less settlement. If these predictions are accurate, the rather large vertical motion detected in NM2 must not be due to settling. More data will be needed to make a complete assessment.

In order to try and provide better stability monitoring 2 to 4 permanent, isolated monuments are proposed. These monuments will provide a stable reference inside the new construction area. They would also aid by reducing the amount of time it takes to reestablish the internal network (See Section 9.2.4) inside the KTeV hall. The nearest existing stable monuments are located at TSB and PS3, which are too far away to be of use.

Figure 9.3.1 shows the design of the monuments. One such monument is initially included in the experimental hall construction package. These monuments are to be isolated from the slab and be deep enough to sharply reduce the effects of weather and building settlement. A deformable material such as bentonite will be used between the outside casing and the monument pillar to prevent motion due to lateral soil pressure. When considering the cost trade-offs of installing these monuments it is important to remember that the next generation of kaon experiments is expected to use the same facility and the alignment tolerances are predicted to be tighter than KTeV if e'/e is measured again.

Another source of possible instability is air gaps under concrete slabs. Good quality control must be maintained during construction to prevent this problem.

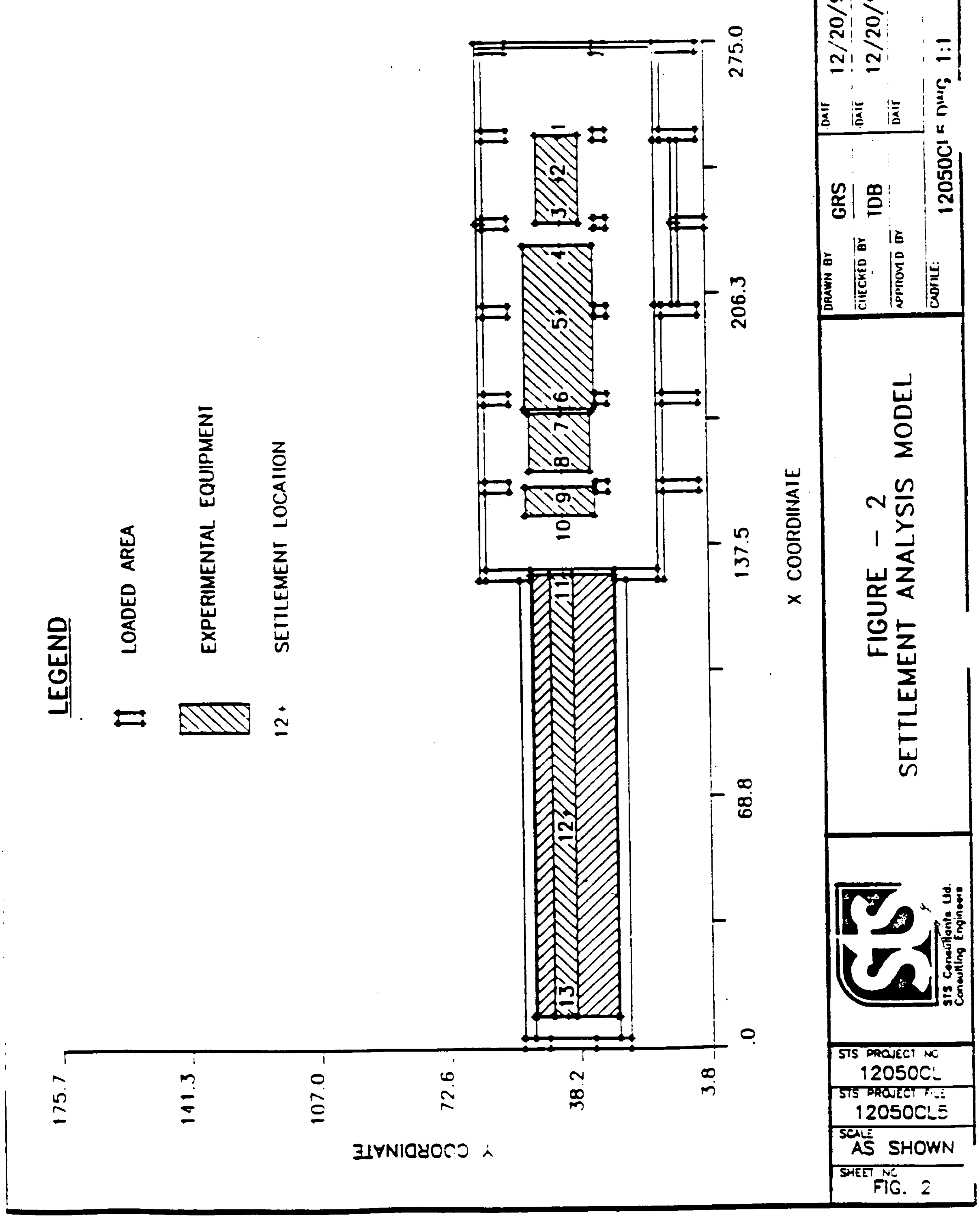

Figure 9.3.3 KTeV hall showing location of analysis points for STS Monte Carlo.

Table 1
KTEV - IMMEDIATE SETTLEMENT
(Initial 6 Month Period)

Settlement Location

Stratum Elevation (ft)	1	2	3	4	5	6	7	8	9	10	11	12	1
723.5-701.9	0.12	0.14	0.10	0.07	0.04	0.06	0.07	0.07	0.06	0.05	0.08	0.12	0
701.9-685.9	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0
685.9-679.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0
Total Settlement (inches)	0.17	0.19	0.15	0.12	0.08	0.10	0.11	0.11	0.10	0.09	0.13	0.18	0

Table 2
KTEV - LONG TERM SETTLEMENT*

Settlement Location

Stratum Elevation (ft)	1	2	3	4	5	6	7	8	9	10	11	12	1
723.5-701.9	0.02	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0
701.9-685.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	[illegible]
685.9-679.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	[illegible]
Total Settlement (inches)	0.03	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	[illegible]

*NOTE: If initial setup period is only 3 months, these long term settlement estimates should be doubled.

Figure 9.3.4 STS Monte Carlo prediction of short and long term settlement of the KTeV experimental hall floor and underlying layers of soil at 13 different points.

Monitoring

As previously discussed, motion due to floor instabilities could exceed tolerances specified for many components. This implies that any precision alignment could be obsolete soon after its completion. Since the most stringent alignment requirements are relative positions, an on-line monitoring system is being considered. Several systems are currently being employed at other labs. Many of them are turnkey commercial systems. These systems would provide information independent of beam data.

Target/Collimator System

Substantive information has been obtained on two commercial systems so far. The first is Hydrostatic Leveling System[81] (HLS) system by Fogale-Nanotech of France. See Figure 9.3.5. This instrument would be used to monitor the elevations of the target collimator system and possibly some detector components. The HLS is a measuring instrument based on the principle of communicating vessels. The instruments would be connected along the KTeV beamline by a water filled tube which determines the reference plane and an air filled tube which guarantees pressure stability along the network. Each probe has a capacitive sensor which measures the water level. The system has a resolution of about 2 μm and a range of 2.5 mm. The non-linearity over the entire range is less than 1 μm.

The system has the advantages of being radiation hard (20 Mrad), more accuracy than required (could be used for next generation kaon experiment), is a commercially available turnkey system, and has been well tested by other labs. It is currently being used very successfully by ESRF and KEK. The ESRF (European Synchrotron Radiation Facility) system automatically realigns the entire ring with the machine on using servo-controlled jacks. The Argonne APS is currently procuring an HLS system so local access should be available soon. A disadvantage of this system is that it only measures vertical displacement.

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[81] **Proceedings of the Third International Workshop on Accelerator Alignment,** CERN, Geneva, 1993

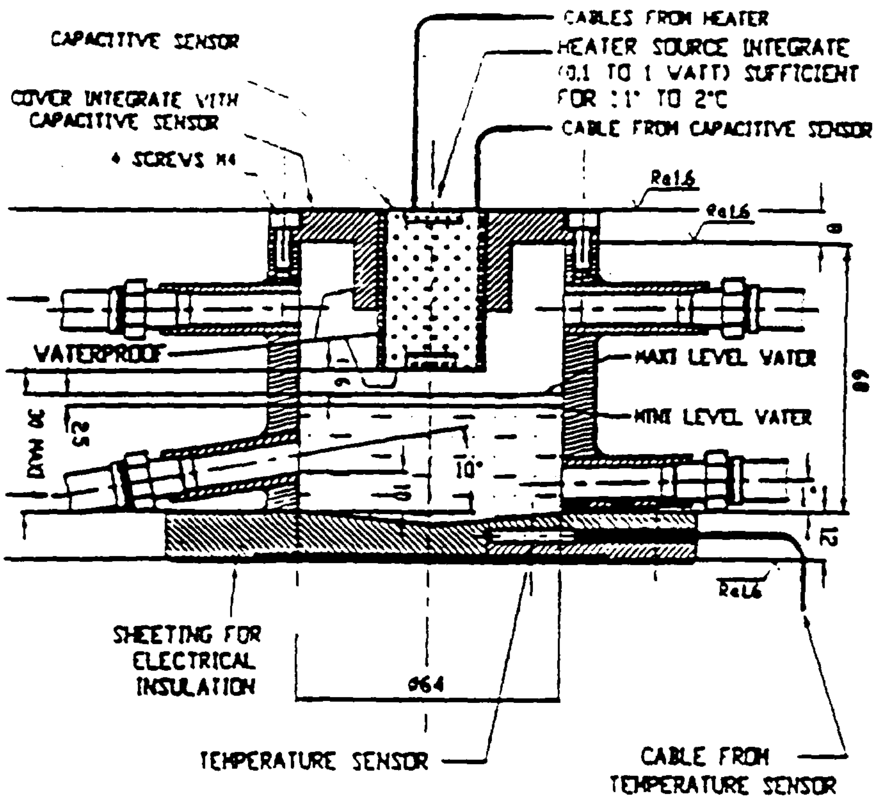


Figure 9.3.5 Cross-section of HLS vessel

It may also be necessary to measure horizontal displacement. There are some systems which are being employed at other labs, but more information needs to be obtained.

Z-calibration of the Detector Elements

One may estimate the floor expansion over the 60 m between the regenerator and the CsI assuming the floor changes temperature uniformly (this is unlikely). Such a calculation yields a projected motion of about 0.4 mm/°F or 3.2 mm over the specified 8°F temperature range in the experimental hall. Since the longitudinal distance between the regenerator, Z-calibrator, and CsI must be known to better than 1 mm, it is proposed that this distance be monitored.

There are inexpensive commercially available systems which meet this requirement. For example, the LEICA DI2002 EDM (Electronic Distance Meter) has an accuracy of ±0.6 mm and costs $11k. It has an RS232 interface which will allow computer readout and control. The SAG group has a LEICA/KERN ME5000 Mekometer which is accurate to 0.2 mm ±0.2 ppm which can be used for calibration. There are other systems available which also meet the specifications.

These systems require an unobstructed line of sight between the elements being measured. According to existing drawings, there are no components which come closer than 3" from the floor to the bottom of the support underneath the beam. According to the manufacturer, this is sufficient clearance to obtain an accurate reading. Field tests will be performed soon. Future detector support designs must not intrude into this 3" space. The regenerator and z-calibrator are in a vacuum tank and the CsI is in a hermetically sealed house. The current proposal involves bringing reference arms outside of the CsI house and vacuum tanks and sighting underneath the spectrometer onto retro-reflectors attached to these arms.

9.3.3 General Alignment and Fiducialization Procedures

Following is a procedure to have a beam or detector element properly fiducialized and aligned. The contact persons are the KTeV alignment coordinators.

1. Each KTeV system manager will provide specific alignment tolerances and specifications.
2. The system manager must then submit engineering drawings which show fiducial points and alignment adjustments for review and comments. This will be an iterative process. For critical tolerance elements, alignment people should be involved from the beginning design phase.
3. Once a plan is in place, any hardware (such as sphere mounts or tooling balls) necessary for the fabrication process will be distributed by the alignment group.
4. The system manager should provide a tentative schedule indicating when the beamline element or detector will be ready to be fiducialized, installed, and aligned.
5. When arrival of the detector or beam element is imminent, The KTeV installation coordinator will then schedule a time and place for the above with the alignment group.
6. Results of each survey and alignment will be provided to the appropriate subsystem managers.

Component Fiducialization

Fiducialization of the components relates their effective beam centerlines to external mechanical points that are accessible to subsequent survey measurements. It is expected that every KTeV beam and detector component will need to be fiducialized. If some elements are being reused and have already been fiducialized once, it is assumed that they will be refiducialized to conform to a system compatible with the laser tracking interferometer. The laser tracker will provide greater accuracy and also reduce the time necessary for component alignment.

Fiducialization plans for each component need to be completed during the engineering phase, prior to fabrication.

At present, we assume that each component will be fiducialized by Fermilab. This will assure that the fiducialization is compatible with the laser tracker platform and conforms with the overall alignment plan. If there is a proposal to independently fiducialize a beam or detector element, the methodology must be reviewed by the Fermilab SAG group.

Since the KTeV beamline and experiment consists of many different types of hardware, a specific fiducialization procedure is currently being developed for each element or class of elements. This will be included in the comprehensive alignment plan which will be presented as a stand alone document. The following are general criteria which must be considered during fiducialization

During fiducialization, the critical parameters must be available in six degrees of freedom to the survey crew. For example, it may be necessary to remove drift chamber windows in order to see the wires or else provide an acceptable mark on the frame which is related to the wires in a very precise way.

All components should be fiducialized so that at least three known mechanical points are visible from one setup which will be located near the alignment and personnel aisle ways provided in all KTeV enclosures. These points must either consist of a permanently fixed sphere mount which will hold a 1.5" retro-reflector for the laser tracker or a hole/guide which will accommodate a sphere mount in a reproducible way. Elements with critical tolerances should have their own permanent spherical mounts. See Section 9.3.4 for specifications and drawing of sphere mounts.

The fiducial hardware should be attached to a rigid structure so that the offsets do not change measurably under stresses such as transport or temperature change. The points should also be located as far apart from each other as possible.

Component Alignment

As discussed earlier, detailed alignment plans will be developed for each class of components. This will be included in the upcoming KTeV Alignment Plan document. Many considerations are already listed in Section 9.1.

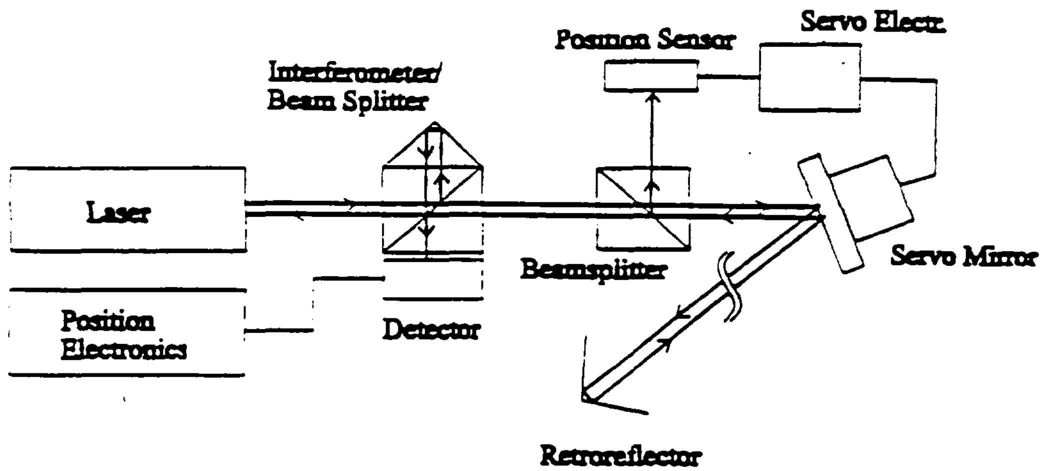
9.3.4 Alignment Hardware Specifications

The geodetic measurements in the surface network are performed with state-of- the-art equipment already being used by the SAG group. These include: high-precision electronic distance measurement with the Kern Mekometer ME5000, angle measurement with Kern E2 theodolites, Wild N3 and Leica N3000 levels, and Trimble 4000SSE Geodetic Survey GPS dual frequency receivers.

Laser Tracking Interferometer

Until recently, the determination of precise three dimensional coordinates in industrial metrology has required two separate instruments or two setups. As instrumentation for the KTeV alignment, we propose to employ the Laser Tracking Interferometer system (the same as intended for the Main Injector). With this system all KTeV devices will be positioned using an interactive and iterative procedure from the layout of coordinates for the magnet support systems to the final smoothing of adjacent components. The automation of measurements and alignment procedures significantly improves their quality and speed compared to that of traditional methods. The SAG group now possesses this hardware. Preliminary tests indicate that the instrument performance is as expected.

The Laser Tracking Interferometer (See Figure 9.3.6) is a dynamic measuring system for three dimensional coordinate determination using a single beam laser interferometer, precise angular encoders, and a servo-tracking system. Simultaneous readings, 1000 times per second, of horizontal/vertical encoders and interferometer counts are calculated and the three dimensional position of the reflector target is displayed in real time.



Schematic of servo-controlled tracking system

SYSTEM SPECIFICATIONS

CMS-3000 Tracker Head:	
	Width: 12.5"
	Height: 23.0"
	Depth: 7.5" min. 9.2" max
	Weight: 80.0 lbs
Remote Power Unit (RPU):	
	Width: 9.5"
	Height: 12.0"
	Depth: 17.0"
	Weight: 25 lbs
Typical Tooling Stand:	Weight: 204 lbs
Assembly Floor Load:	Average = 37.5 lbs/sq. ft
Repeatability:	At least 5 ppm of measurement
Resolution:	Angular = 1 arc-second per angular unit Radial = from 0.5 to 5 microns per distance unit
Velocity:	From 1 to 6 meters/sec.
Acceleration:	> 2 g's
Distance Range:	0.17 meters (min.) to 30 meters (max.)
Elevation Range:	± 55 degrees
Azimuth Range:	>270 degrees

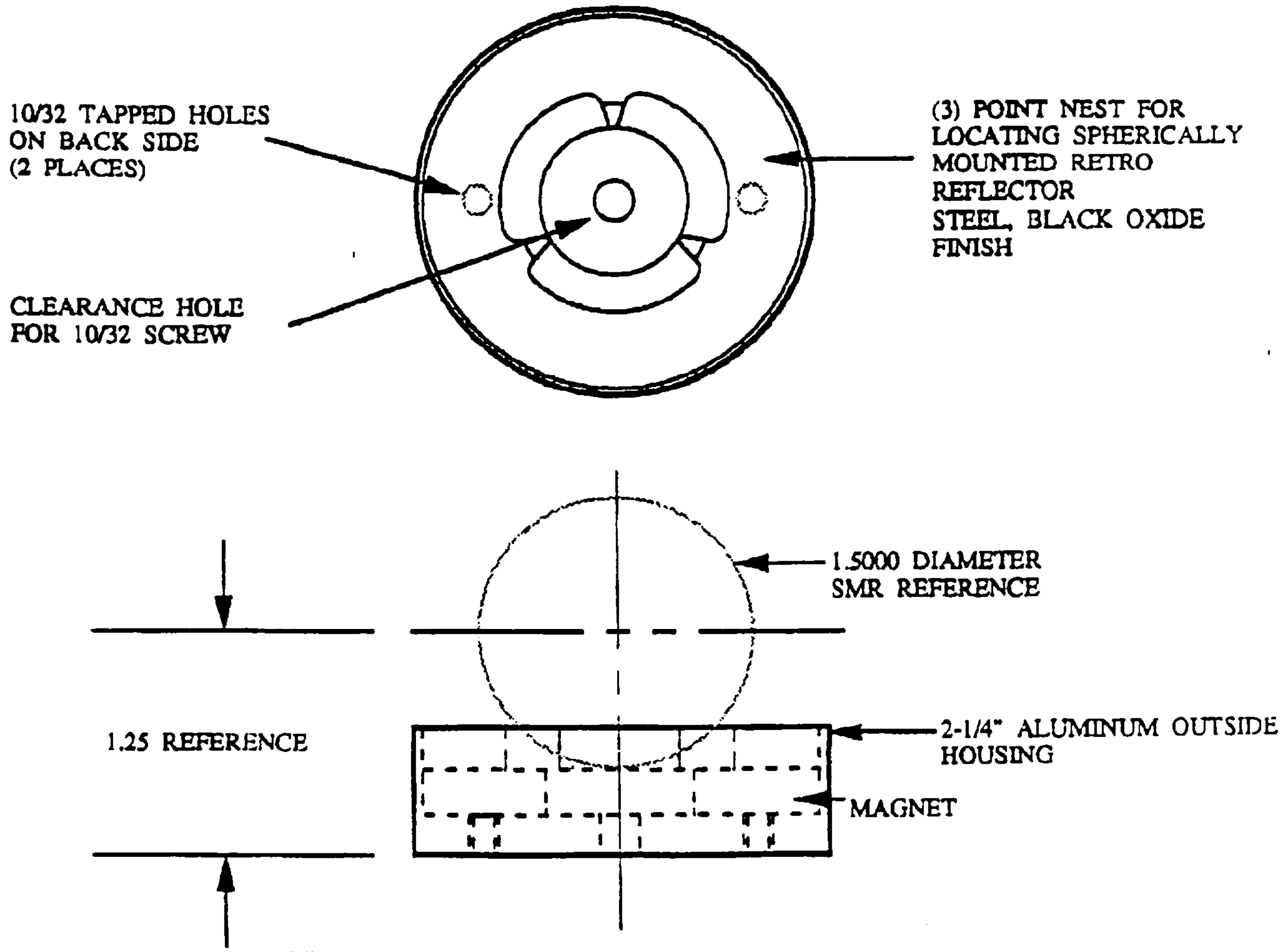
Figure 9.3.6 Schematic of Chesapeake Laser Tracking Interferometer

These coordinates are continuously compared with the theoretical coordinates and the resultant difference coordinate vector is displayed also in real time. For 30 microns interferometer accuracy and 1 arc second angular resolution, the Laser Tracker is estimated to provide measurements to the component fiducials within 0.1 mm range. This automatic transmission and handling of measurements and alignment parameters largely excludes the usual risk of operational errors during routine work.

The Laser Tracker comes with a PC compatible computer system for computation, control, and data logging.

Sphere Mounts

Sphere mounts are magnetic sockets designed to hold the retro-reflector for the Laser Tracker. They can also accommodate more conventional instruments. These will be mounted on most of the detector and beam elements for referencing. They come in several varieties, samples of which are shown in Figure 9.3.7. The 2.25" heavy-duty sphere mount is the most economical ($57) and will probably suffice for most applications. It is machined to slightly lower centering tolerances than the standard 1.5" mount ($135) but the reproducibility is more important than the centering tolerance.



1.5 SPHERE MOUNT

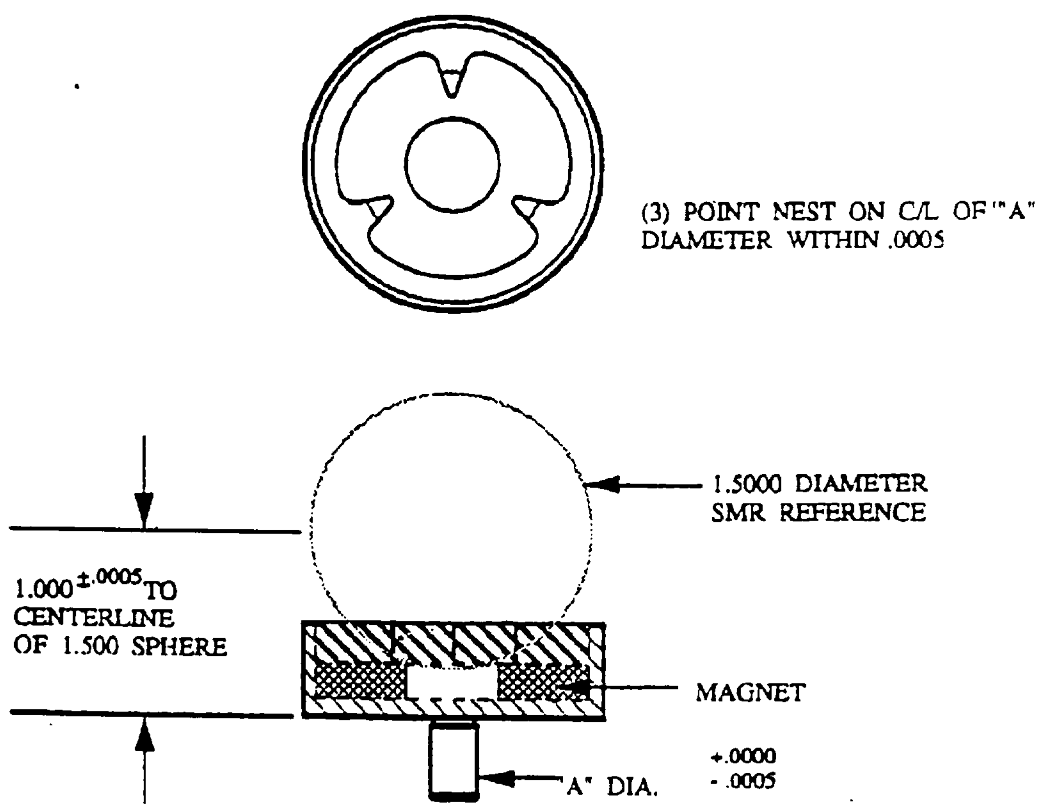


Figure 9.3.7 Schematic of sphere mounts designed to hold corner reflectors for the

APPENDIX 1

KTEV PRIMARY BEAM SHEET

NM TRANSPORT 1-APR-94
0 1000 GEV

Z CENT.	X CENT.	Y CENT.	POSITION CODE	ELEMENT CODE	POWER SUPPLY	B(KG) OR (KG/IN)
3184.00	-26.21	732.90	NMMUPT			
3185.74	-26.27	732.89	NM1BPM1			
3187.24	-26.31	732.89	NM1BPM2			
3188.49	-26.35	732.89	NM1WC			
3193.99	-26.51	732.88	NM1V-1	FRD11679 5-1.5-120 V-BEND	NM1U	18.688
3204.99	-26.84	732.87	NM1V-2	FRD11414 5-1.5-120 V-BEND	NM1U	18.688
3211.23	-27.02	732.87	NM1H	FRD11489 4-4-30 H-TRIM	NM1H	0.000
3620.01	-39.16	733.21	NM2USW	NM2 USTREAM WALL		
3620.57	-39.18	733.21	NM2USP	NM2 UPSTREAM PIPE		
3621.32	-39.20	733.22	NM2BPM1			
3622.82	-39.24	733.22	NM2BPM2			
3624.07	-39.28	733.22	NM2WC1			
3625.90	-39.33	733.22	NM2SEM			
3637.21	-39.68	733.24	NM2EU-1	B2	NM2EU	17.046
3658.20	-40.36	733.29	NM2EU-2	B2	NM2EU	17.046
3670.44	-40.78	733.33	NM2V-1	Vertical TRIM	NM2V	0.000
3677.69	-41.03	733.36	NM2Q1-1	4Q120	NM2Q1	4.879
3689.18	-41.43	733.40	NM2Q1-2	4Q120	NM2Q1	4.879
3700.68	-41.84	733.45	NM2Q1-3	4Q120	NM2Q1	4.879
3718.66	-42.47	733.52	NM2Q2-1	4Q120	NM2Q2	-5.005
3730.16	-42.87	733.57	NM2Q2-2	4Q120	NM2Q2	-5.005
3741.65	-43.27	733.61	NM2Q2-3	4Q120	NM2Q2	-5.005
3753.14	-43.68	733.66	NM2Q2-4	4Q120	NM2Q2	-5.005
3769.13	-44.24	733.71	NM2D1-1	B2	NM2D1	17.893
3790.12	-44.97	733.72	NM2D1-2	B2	NM2D1	17.893
3811.11	-45.71	733.67	NM2D2	B2	NM2D2	13.957
3823.35	-46.14	733.62	NM2V-2	Horizontal TRIM	NM2H	0.000
3825.60	-46.22	733.61	NM2WC2			
3836.09	-46.59	733.56	NM2WC3			
3838.09	-46.66	733.55	NM2TGT			
3838.09	-46.66	733.55	NMSEC			
4059.77	-54.43	733.51	NM2DSW			
4230.40	-60.41	733.47	NM3	3. 392.54782 'NM3' ;		

1NM TRANSPORT 1-APR-94

NAME	TYPE	FIRE DEPT	STATION	EASTING		NORTHING			
	HEIGHT	AZIMUTH	SLOPE	ROLL					
NMMUPT	DRIFT		39245.648	314.575	38207.941	8797.834	1 42 1	0 -8 17	0 0 -3
NM1BPM1	DRIFT		39257.648	314.931	38219.938	8797.806	1 42 1	0 -8 17	0 0 -3
NM1BPM1	DRIFT		39275.648	315.466	38237.930	8797.762	1 42 1	0 -8 17	0 0 -3
NM1BPM2	DRIFT		39275.648	315.466	38237.930	8797.762	1 42 1	0 -8 17	0 0 -3
NM1BPM2	DRIFT		39293.648	316.000	38255.922	8797.719	1 42 1	0 -8 17	0 0 -3
NM1WC	DRIFT		39293.648	316.000	38255.922	8797.719	1 42 1	0 -8 17	0 0 -3
NM1WC	DRIFT		39305.652	316.356	38267.914	8797.689	1 42 1	0 -8 17	0 0 -3
NM1V-1	5-1.5-120	11679	39305.652	316.356	38267.914	8797.689	1 42 1	0 -8 17	89 59 57
	SAGITTA CORRECT			316.356	38267.914	8797.686			
NM1V-1	5-1.5-120	11679	39425.648	319.917	38387.863	8797.503	1 42 1	0 -2 25	89 59 57
	SAGITTA CORRECT			319.917	38387.863	8797.499			
NM1V-2	5-1.5-120	11414	39437.648	320.273	38399.855	8797.495	1 42 1	0 -2 25	89 59 57
	SAGITTA CORRECT			320.273	38399.855	8797.491			
NM1V-2	5-1.5-120	11414	39557.648	323.833	38519.805	8797.513	1 42 1	0 3 27	89 59 57
	SAGITTA CORRECT			323.833	38519.805	8797.509			
NM1H	4-4-30	11489	39557.648	323.833	38519.805	8797.513	1 42 1	0 3 27	0 0 -3
	SAGITTA CORRECT			323.833	38519.805	8797.513			
NM1H	4-4-30	11489	39587.648	324.724	38549.789	8797.543	1 42 1	0 3 27	0 0 -3
	SAGITTA CORRECT			324.724	38549.789	8797.543			
NM2USW	DRIFT		44480.117	469.898	43440.102	8802.513	1 42 1	0 3 32	0 0 -3
NM2USP	DRIFT		44486.922	470.100	43446.898	8802.521	1 42 1	0 3 32	0 0 -3
NM2BPM1	DRIFT		44486.922	470.100	43446.898	8802.521	1 42 1	0 3 32	0 0 -3
NM2BPM1	DRIFT		44504.918	470.635	43464.895	8802.538	1 42 1	0 3 32	0 0 -3
NM2BPM2	DRIFT		44504.918	470.635	43464.895	8802.538	1 42 1	0 3 32	0 0 -3
NM2BPM2	DRIFT		44522.914	471.169	43482.887	8802.556	1 42 1	0 3 32	0 0 -3
NM2WC1	DRIFT		44522.914	471.169	43482.887	8802.556	1 42 1	0 3 32	0 0 -3
NM2WC1	DRIFT		44534.914	471.525	43494.883	8802.568	1 42 1	0 3 32	0 0 -3
NM2SEM	DRIFT		44534.914	471.525	43494.883	8802.568	1 42 1	0 3 32	0 0 -3
NM2SEM	DRIFT		44566.660	472.467	43526.609	8802.602	1 42 1	0 3 32	0 0 -3
NM2EU-1	BEND		44566.660	472.467	43526.609	8802.602	1 42 1	0 3 32	-30 24 3
	SAGITTA CORRECT			472.454	43526.609	8802.594			
NM2EU-1	BEND		44806.660	479.911	43766.492	8803.036	1 51 16	0 8 57	-30 24 2
	SAGITTA CORRECT			479.898	43766.492	8803.029			
NM2EU-2	BEND		44818.660	480.299	43778.492	8803.068	1 51 16	0 8 57	-30 24 2
	SAGITTA CORRECT			480.287	43778.492	8803.061			
NM2EU-2	BEND		45058.656	488.387	44018.352	8803.883	2 0 30	0 14 22	-30 24 0
	SAGITTA CORRECT			488.375	44018.352	8803.875			
NM2V-1	BEND		45070.656	488.808	44030.344	8803.933	2 0 30	0 14 22	89 59 60
	SAGITTA CORRECT			488.808	44030.344	8803.933			
NM2V-1	BEND		45100.656	489.859	44060.324	8804.058	2 0 30	0 14 22	89 59 60
	SAGITTA CORRECT			489.859	44060.324	8804.058			
NM2Q1-1	4Q120		45112.656	490.280	44072.316	8804.108	2 0 30	0 14 22	0 0 0
NM2Q1-1	4Q120		45232.656	494.485	44192.242	8804.609	2 0 30	0 14 22	0 0 0
NM2Q1-2	4Q120		45250.652	495.116	44210.230	8804.686	2 0 30	0 14 22	0 0 0
NM2Q1-2	4Q120		45370.652	499.321	44330.156	8805.187	2 0 30	0 14 23	0 0 0
NM2Q1-3	4Q120		45388.648	499.952	44348.145	8805.262	2 0 30	0 14 23	0 0 0
NM2Q1-3	4Q120		45508.648	504.157	44468.070	8805.764	2 0 30	0 14 23	0 0 0
NM2Q2-1	4Q120		45604.648	507.521	44564.012	8806.165	2 0 30	0 14 23	0 0 0
NM2Q2-1	4Q120		45724.648	511.727	44683.941	8806.667	2 0 30	0 14 23	0 0 0
NM2Q2-2	4Q120		45742.645	512.357	44701.930	8806.742	2 0 30	0 14 23	0 0 0
NM2Q2-2	4Q120		45862.645	516.563	44821.855	8807.244	2 0 30	0 14 23	0 0 0
NM2Q2-3	4Q120		45880.641	517.193	44839.844	8807.319	2 0 30	0 14 23	0 0 0
NM2Q2-3	4Q120		46000.641	521.399	44959.770	8807.821	2 0 30	0 14 23	0 0 0
NM2Q2-4	4Q120		46018.637	522.029	44977.758	8807.896	2 0 30	0 14 23	0 0 0
NM2Q2-4	4Q120		46138.637	526.235	45097.684	8808.399	2 0 30	0 14 23	0 0 0
NM2D1-1	BEND		46150.637	526.655	45109.676	8808.449	2 0 30	0 14 23	89 59 60
	SAGITTA CORRECT			526.655	45109.676	8808.464			
NM2D1-1	BEND		46390.637	535.066	45349.531	8809.061	2 0 30	0 3 9	89 59 60
	SAGITTA CORRECT			535.066	45349.531	8809.075			
NM2D1-2	BEND		46402.637	535.486	45361.520	8809.072	2 0 30	0 3 9	89 59 60
	SAGITTA CORRECT			535.486	45361.520	8809.087			
NM2D1-2	BEND		46642.633	543.897	45601.375	8808.900	2 0 30	0 -8 5	89 59 60
	SAGITTA CORRECT			543.897	45601.375	8808.915			
NM2D2	BEND		46654.637	544.318	45613.367	8808.872	2 0 30	0 -8 5	89 59 60
	SAGITTA CORRECT			544.318	45613.367	8808.884			
NM2D2	BEND		46894.633	552.728	45853.215	8808.001	2 0 30	0-16 51	89 59 60

	SAGITTA CORRECT		552.728	45853.215	8808.013			
NM2V-2	BEND	46906.633	553.149	45865.203	8807.941	2 0 30	0-16 51	0 0 0
	SAGITTA CORRECT		553.149	45865.203	8807.941			
NM2V-2	BEND	46936.633	554.200	45895.184	8807.795	2 0 30	0-16 51	0 0 0
	SAGITTA CORRECT		554.200	45895.184	8807.795			
NM2WC2	DRIFT	46948.633	554.620	45907.176	8807.735	2 0 30	0-16 51	0 0 0
NM2WC3	DRIFT	47074.633	559.036	46033.094	8807.118	2 0 30	0-16 51	0 0 0
NM2TGT	DRIFT	47098.633	559.877	46057.082	8807.001	2 0 30	0-16 51	0 0 0
NMSEC	DRIFT	47098.633	559.877	46057.082	8807.001	2 0 30	0 0 0	0 0 0
NM2DSW	DRIFT	49760.414	653.157	48717.223	8807.011	2 0 30	0 0 2	0 0 0
NM3	DRIFT	51809.211	724.956	50764.758	8807.037	2 0 30	0 0 4	0 0 0

Beam Sheet Program Version used in this job:

Machine: RDIV01 Version: RELEASE

Source File	Version
BSHEET	910820.143746
BSH	910820.143746
TRM	910820.143955
TRS	910524.113407
TRIN	910820.143901

APPENDIX 2

PRECLUDING DOWNSTREAM KTEV PRIMARY BEAM TRANSPORT

This appendix describes in more detail the methods used in setting the interlock presented in Section 3.1.1 to prevent the primary beam at 800 GeV from exiting the KTeV Target Pile. The precise values of the current interlocks depend on the final configuration of the Primary Beam line, but the methodology presented here is applicable in case this should change.

To prevent the beam from exiting the KTeV Target Pile, we specifically prevent an 800 GeV primary proton from entering the neutral beam aperture of NM2S2, the first major element downstream of the KTeV Target Pile. This will be done through current interlocks on NM2EU, NM2Q1, NM2Q2 and the AVB system, and careful alignment and configuration control including position "RED TAGS" on NM1U and NM2EU magnet strings.

The calculations for these interlocks were done to prevent a primary proton having the maximum possible deviation from the beam centerline from leaving NM2BD (the NM2 Beam Dump). The maximum allowed deviations from the primary beam centerline were determined by the positions and apertures of NM1U and NM2EU which act as fixed collimators to place a primary proton on the edge of the aperture of the Beam Dump. The horizontally sweeping NM2S1 magnet (the Target Sweeping Magnet) running at the nominal 5kG will not prevent beam from being horizontally steered into the neutral channel of the secondary beam, so the approach was to provide adequate protection by relying on the limits to vertical steering only. For a schematic of the apertures in NM1 and NM2 for the KTeV Primary Beam, see Figure A3.1 (this figure is present in Section 3.1.1 as Figure 3.1.1). The figure includes the extreme cases which defined the above interlocks. An elevation view of the KTeV Target Hall components is given in Figure A3.2. This Figure includes the minimum nominal primary beam centerline, and the most extreme trajectory allowed by the collimators that a beam particle can take in the NM2 Beam Dump aperture with the above proposed interlocks.

The angle from the target to the lower aperture edge on the upstream face of the NM2 Beam Dump is -2 mrad, but to accommodate major accidental deviations in position and angle of incoming primary protons, we set the interlock on the AVB system to $I_{NM2D1} + 0.5*I_{NM2D2} \geq 4630$ amps, such that the primary beam is deflected by the AVB system to an angle of at least -4.0 mrad into the Beam Dump. This angle then defines the maximum excursion that a beam particle's position and angle is allowed to have before it enters the Beam Dump aperture. Any such change to place it greater than 0.512" above the primary beam centerline at the upstream face of the Beam Dump (20.3 feet from the target, 15 feet long) will place it into the aperture of the Beam Dump. Any trajectory change to put a +1.23" displacement to a particle at the downstream end of the Beam Dump would result in the proton exiting the dump through the aperture, entering the aperture of NM2S2, and possibly impacting in downstream enclosures. This trajectory will be precluded by the proposed interlocks.

The change in vertical beam position and angle at the downstream end of the Beam Dump is influenced by quadrupole steering in NM2. The position change from the nominal trajectory can be written as a transformation of the position and angle of the beam particle from NM2EU to the downstream end of the dump:

$$y_{Dump} = R_{33} y_{NM2} + R_{34} \dot{y}_{NM2}$$

Since the angle that a beam particle can take to get into the aperture of the Beam Dump ($\dot{y}_{Dump}$) can be limited by the aperture of NM2S1 (y_{NM2S1}), we can see if we need to limit the angle of the proton at NM2EU. We can then write:

$$\dot{y}_{NM2} = \frac{\dot{y}_{Dump} - R_{43} y_{NM2}}{R_{44}}$$

where:

$$\dot{y}_{Dump} = \frac{y_{NM2S1} - y_{Dump}}{36.45'}$$

with 36.45' the distance between the upstream end of NM2S1 and the Beam Dump.

We will use the NM2EU B2 dipole string as a collimator to limit y_{NM2} to be less than ±1.5" from the nominal trajectory. As can be seen in Figure 2.4.4, the beam at this point is expected to be about 0.6 cm at 1 sigma (0.557" full width at half maximum), giving ample of room for normal primary beam transport through the magnets. Within the upstream aperture limits of the Target Sweeping Magnet, y_{NM2S1} can be varied for given values of R_{43} and R_{44} until we find the largest value of y_{Dump}, as done in Figure A3..3. The corresponding maximum $\dot{y}_{Dump}$ change is shown in Figure A3.4. This is the worst possible beam trajectory for this case of only controlling the configuration of NM2EU, NM2S1, and NM2BD. The values of R_{33} and R_{34} are found by varying the horizontal and vertical focal length of the NM2Q1-NM2Q2 quadrupole pair. We can change the currents of both magnets such that we vary the focal length of one plane and hold the focal length in the other plane constant, effectively decoupling the horizontal and vertical planes.

Looking at Figure A3.3, we can see that the maximum possible position change is not within the 1.23" distance to the lower edge of the aperture if the angles are limited only by the apertures of NM2EU and the Target Sweeping Magnet. Also, since the Primary Collimator is moveable in the vertical plane, it cannot be used as a trajectory-limiting aperture for safety purposes. NM2S3 would be the next downstream device that could be used to limit the primary beam trajectory. The trajectory of the beam passing through its aperture from the upstream end of the Target Pile will need to have a position change of more than +1.96" at the downstream of the NM2 Beam Dump, and an angle change more than +2.42 mrad, to allow it into NM3. As can be seen in Figures A3.2 and A3.3, the ranges for this case would allow this to happen. This possibility will be prevented by including current interlocks and the position "RED TAGS" on NM2 elements.

We also need to limit the angle of the beam entering the NM2 quadrupoles such that we can prevent beam from entering the aperture of NM2S2. The angle of the proton downstream of NM2EU will change due to current changes in the magnet current in NM2 and position changes at NM1 relative to position changes in NM2. We can write:

$$\dot{y}_{NM2} = \dot{y}_{NM2Mag} + (y_{NM1} - y_{NM2})/L$$

where L is the distance between the limiting aperture in NM1 and the limiting aperture in NM2.

We can change the angle due to magnet current changes in NM2 ($\dot{y}_{NM2Mag}$) through NM2V and NM2EU. Due to tuning requirements in the beam line, we need to have as much freedom as possible in changing the current in NM2V, a 4-4-30 trim with a maximum angle change ±0.14 mrad. If we interlock the NM2EU current such that it can vary ±68 amps from the nominal value, the most that $\dot{y}_{NM2Mag}$ can change due to the change of NM2EU current is ±0.060 mrad. Therefore, the most that $\dot{y}_{NM2Mag}$ can change due to magnet current changes in NM2 is ±0.20 mrad.

We can also use the NM1U dipole string as a ±1.5″ collimator to limit the vertical position changes in NM1 (y_{NM1}) to be less than ±2" (±1.5″ vertical aperture with a ±0.5″ alignment tolerance included), defining L=440' (13.4 cm/mrad). The magnets' tolerances of ±0.5" in the vertical position relative to NM2EU provides an included safety margin of 0.10″ in the beam deviation from the nominal path at the downstream end of the Beam Dump. The use of NM1U and NM2EU as limiting apertures will require that the positions of these magnets must be "RED TAGGED", movable only though explicit instruction of the Radiation Safety Officer and Beam Line Physicist.

Then, for given values of R_{33} and R_{34}, we can vary y_{NM2}, y_{NM1}, and $\dot{y}_{NM2Mag}$ within the allowable limits until we find the largest value of y_{Dump}. This is the worst possible beam trajectory for this case with the proposed interlocks listed at the beginning of this section. Again, the values of R_{33} and R_{34} are found by varying the horizontal and vertical focal length of the NM2Q1-NM2Q2 quadrupole pair.

We can set the current limits on NM2Q1 and NM2Q2 by looking at the maximum position displacement for a primary proton at the end of the NM2 Beam Dump as a function of the inverse of the quadrupole pair's focal length (R_{43} transfer matrix element) in the vertical plane, taking into account displacement due to the bending magnets mentioned above. Using the distance to the aperture (1.23") as the limit that we will allow the particle to travel, we set the quadrupoles' current limits as a linear combination of the two quadrupole string currents. Appropriate limits are set as shown on Figure A3.5, a plot of NM2Q2 field current vs. NM2Q1 field current for different vertical and horizontal inverse focal lengths.

The limits shown in Figure A3.5 are $0.217 * I_{NM2Q1} + I_{NM2Q2} = -2.95 \pm 0.45$ kG/in @ 800 GeV (-567 ± 86 amps), where the -2.50 kG/in @ 800 GeV value is the upper limit on the R_{21} and R_{43} matrix element, and the -3.40 kG/in @ 800 GeV value is the lower limit. Placing a limit on the NM2Q1 power supply will prevent the proton from being directed into the aperture through quadrupole steering at high currents. The vertical dashed line shown in Figure A3.5 limiting I_{NM2Q1} is at 5.0 kG/in @ 800 GeV, or 1011 amps. Figure A3.6 shows these limits on a plot of maximum beam position change at the downstream end of the Beam Dump vs. the inverse vertical focal length (R_{43}) at different horizontal focal lengths (R_{21}). The expected operating settings are at R_{21} = -0.217 mrad/cm and R_{43} = -0.557 mrad/cm, well within the allowed range shown on this graph.

The extreme position changes allowed with these interlocks are shown on Figures A3.1 and A3.2. Extrapolating the rays to the downstream end of NM2S3, we find that the maximum deviation allowed is 1.273" below the neutral beam centerline at that point. Since the magnet's vertical aperture is ±0.787", this puts the maximum position change 0.486" below the lower limiting aperture. This gives a 0.486" safety margin at the end of NM2S3 to prevent primary protons from impacting in NM3 and the KTeV Experimental Hall.

Beam pulses in which the beam activates the critical devices for that part of the beam line due to intensity or magnet interlock trips during a beam spill may occur as accident pulses. In the case of KTeV, the primary critical device protecting the beam line is MuLam, and the secondary device are the MuBends. We can safely say that the beam is lost in NM1U once the MuLam is below 4% of its set-to value, or 7.14 milliseconds using a time constant for

MuLam of 0.175 seconds. MuLam splits the beam horizontally, so its tripping off has no bearing on the interlock system outlined above. However, if the trip is due to a magnet interlock outlined above, the time it takes to lose the beam upstream of NM2 does have a bearing on the safety of the system.

If NM2EU trips off, the beam will take a lower and more westward trajectory than nominal, putting the Primary beam lower at the Beam Dump. If NM2Q1 or NM2Q2 trip off, the magnet will be at 99.7% of the value it was running at before the trip when the beam is lost due to MuLam, using a time constant for the 4Q120s of 2.04 seconds. As can be seen in Figure A3.2, the primary beam may enter the aperture of NM2S2, but it will not exit the aperture of NM2S3 in this accident case.

If one of the magnet strings in the AVB system trip off, the beam will take a more upward trajectory while the magnet field is decaying. With the B2 magnets having a time constant of 0.75 seconds, in the 0.00714 seconds it will take for the beam to be lost upstream, the AVB system will bend 0.95% less than before the trip, which corresponds to a maximum upwardly angle change in the beam of 75 μrads. At the downstream end of NM2S3, this is 0.134". Since the safety margin at this point for the shallowest allowed beam is 0.486", the beam will not enter the neutral beam line aperture.

Primary beam must not be transported through the neutral beam channel into the KTeV experimental hall since it is designed only to accept *secondary beam of much lower energy and intensity. In addition beam line* elements downstream of the targeting station within NM2 are not set to transport 800 GeV particles. Because of this, the introduction of primary beam into the neutral beam channel could result in higher than normal losses downstream of the targeting station. This could cause significant residual radiation dose rates, contamination, and increased air activation. Routine maintenance and unscheduled repairs would be more difficult. The goal to insure that the 800 GeV primary beam is confined to the well-shielded target station has been achieved in selecting the interlocks described in Section 3.1.1.

KTeV Primary Beamline Apertures - NM1 through NM2
Elevation view

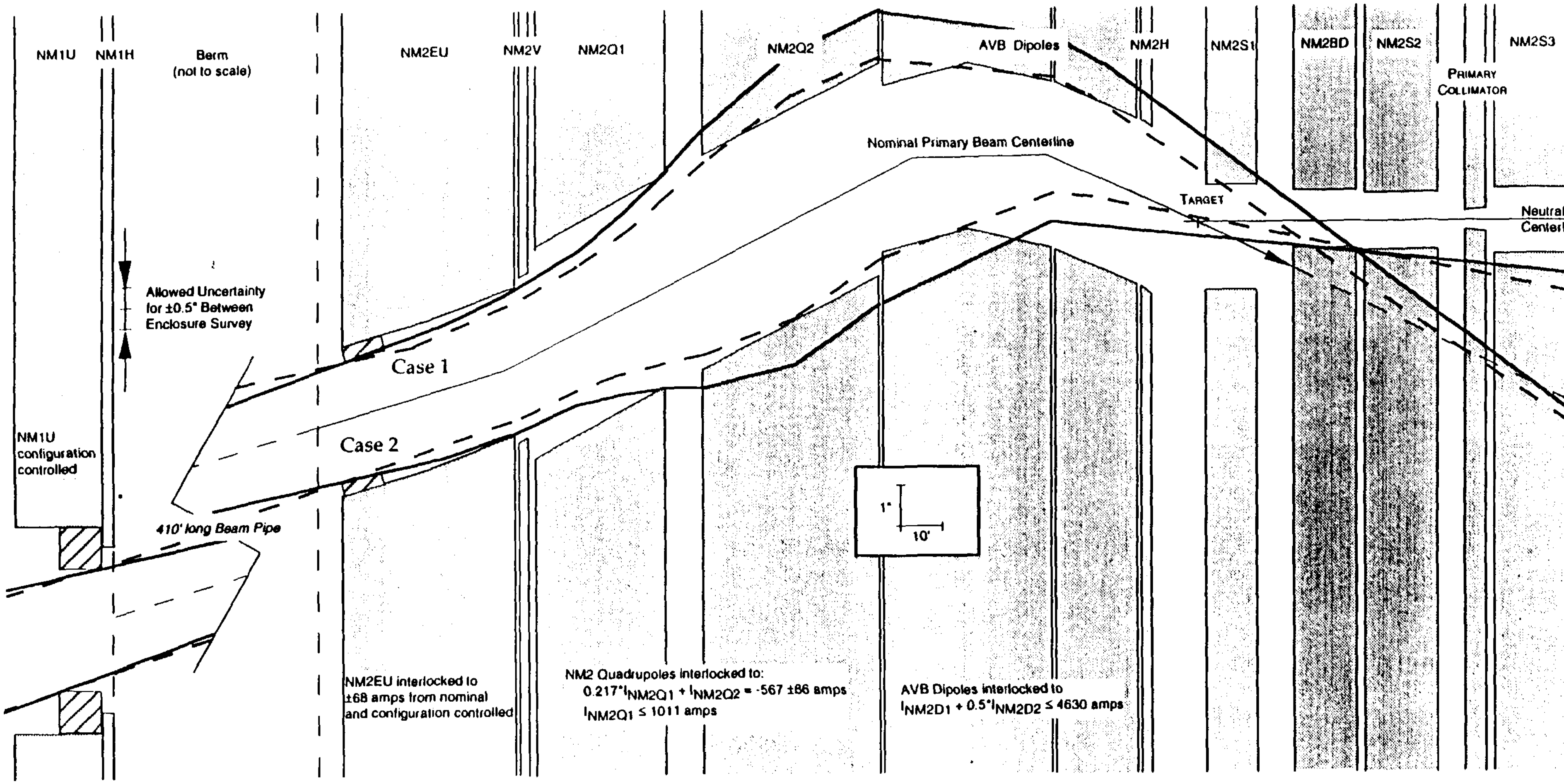


Figure A3.1: KTeV Primary Apertures. Shown here are the vertical apertures for the magnets from NM1 to the KTeV Target Hall, with the Nominal Primary Beam Centerline shown for the path of primary beam with the AVB system set to bend the beam to -4.00 mrads at the Target. The two extremes shown as thick solid lines are for beam entering NM2 at ±0.6629 mrads relative to the nominal beam trajectory, the beam paths from the lower aperture limit of either NM1U or NM2EU to the upper aperture limit of the other. The thick dashed lines are for beam entering at ±0.0947 mrad relative to the nominal beam trajectory, the beam path due to the allowed survey tolerance between enclosures, staying on the same side of the nominal beam along the edge of the NM1U and NM2EU apertures. The solid beam paths cross each other in the beam pipe region between NM1 and NM2. The magnets are set to produce the maximum allowed deviation from the nominal with these extremes at the downstream end of the Beam Dump.

Case 1 is for the NM2 quadrupoles set to R_{21}=-0.500 mrad/cm and R_{43}=-0.430 mrad/cm.

Case 2 is for the NM2 quadrupoles set to R_{21}=-0.500 mrad/cm and R_{43}=-0.687 mrad/cm.

For both cases, the AVB system is set to its minimum limit, and NM2EU & NM2V to their maximum upward bending limits. The range for allowable quadrupole current settings lie between these extremes. Note that the AVB and NM2S1 magnets are not configuration controlled in this scheme. An elevation view of the KTeV Target Hall components is given in Figure A3.2.

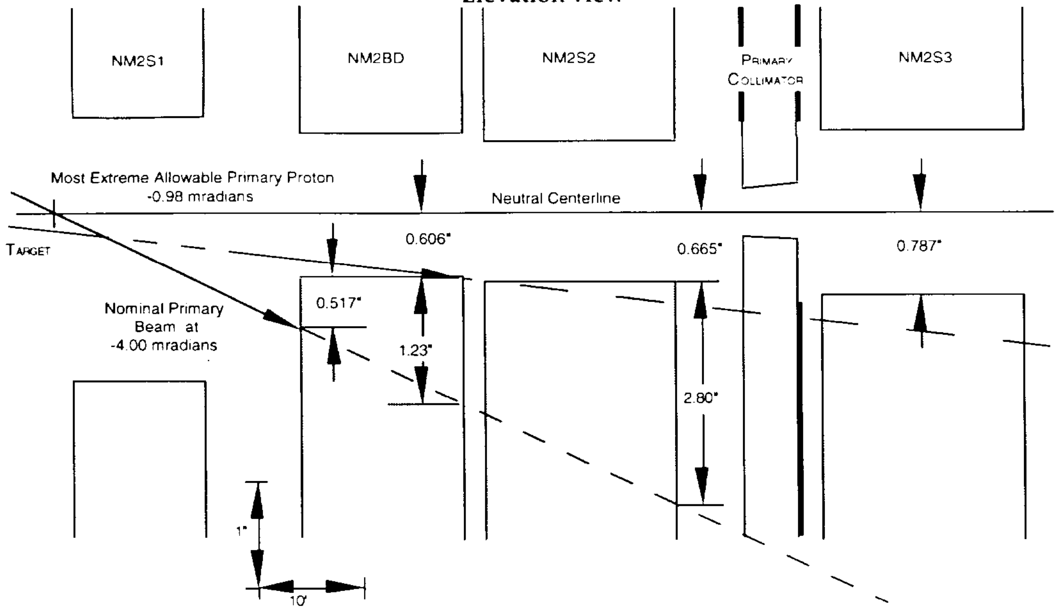


Figure A3.2: KTeV Target Hall Beam Dump System Apertures in the Elevation View. The KTeV Target Pile contains the NM2 Target, NM2S1, and NM2BD, with the upstream edge defined by the Target, and the downstream edge defined by the Beam Dump. This Figure also shows the minimum nominal primary beam path and the most extreme primary beam trajectory allowed by the interlocks described in the text.

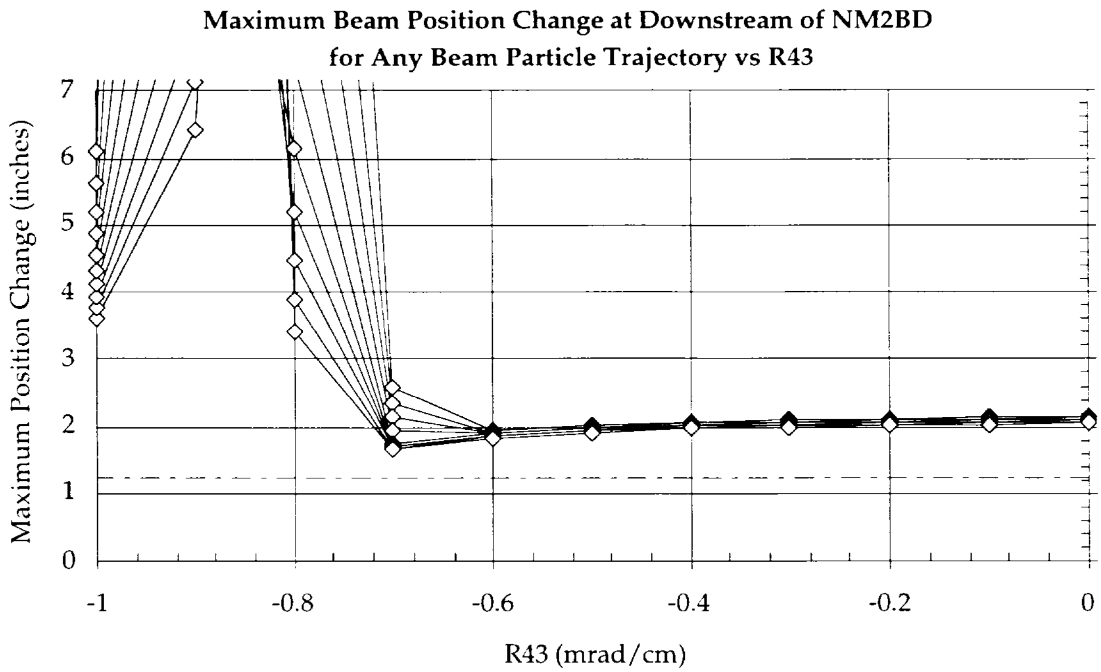


Figure A3.3: Maximum Beam Position Change at Downstream of NM2BD for Any Primary Beam Particle Trajectory vs. R_{43}. The dashed line signifies the farthest upward position change that a primary proton can have and still impact on the Beam Dump. The multiple lines show the result for various R_{21}, ranging from -0.050 mrad/cm along the upper track, and -0.50 mrad/cm along the lower track. The positions are limited only by the aperture restrictions on NM2EU, NM2S1, and NM2BD (see text).

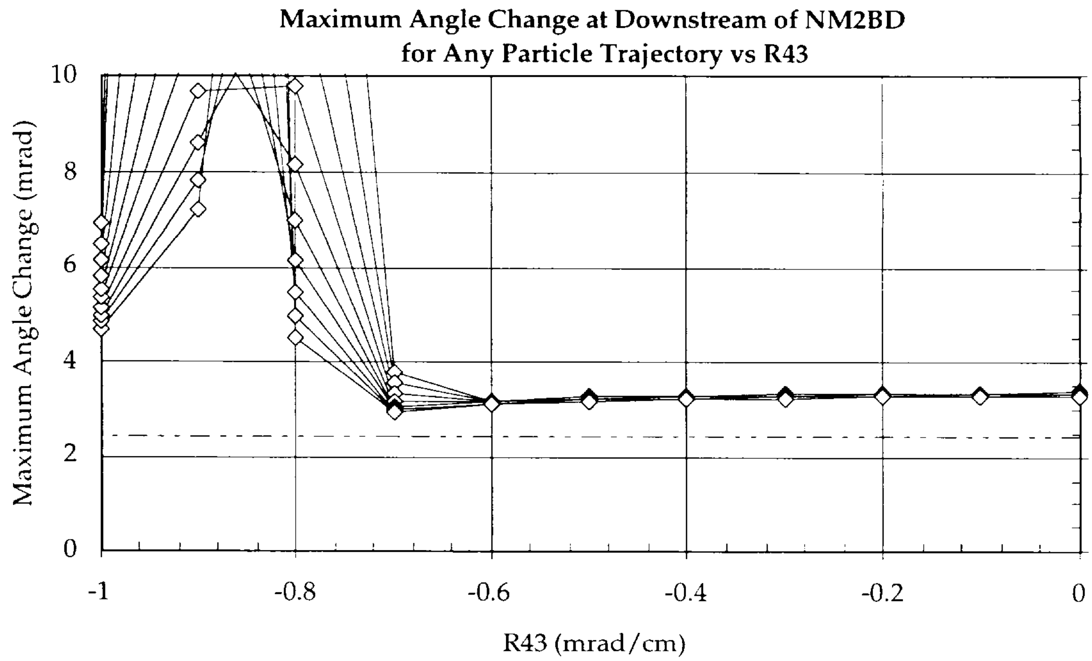


Figure A3.4: Maximum Beam Angle Change at Downstream of NM2BD for Any Primary Beam Particle Trajectory vs. R_{43}. The multiple lines show the result for various R_{21}, ranging from -0.050 mrad/cm along the upper track, and -0.50 mrad/cm along the lower track. The dashed line indicates the limit of a maximum 2.42 mrad angle change. The angles are limited only by the aperture restrictions on NM2EU, NM2S1, and NM2BD (see text).

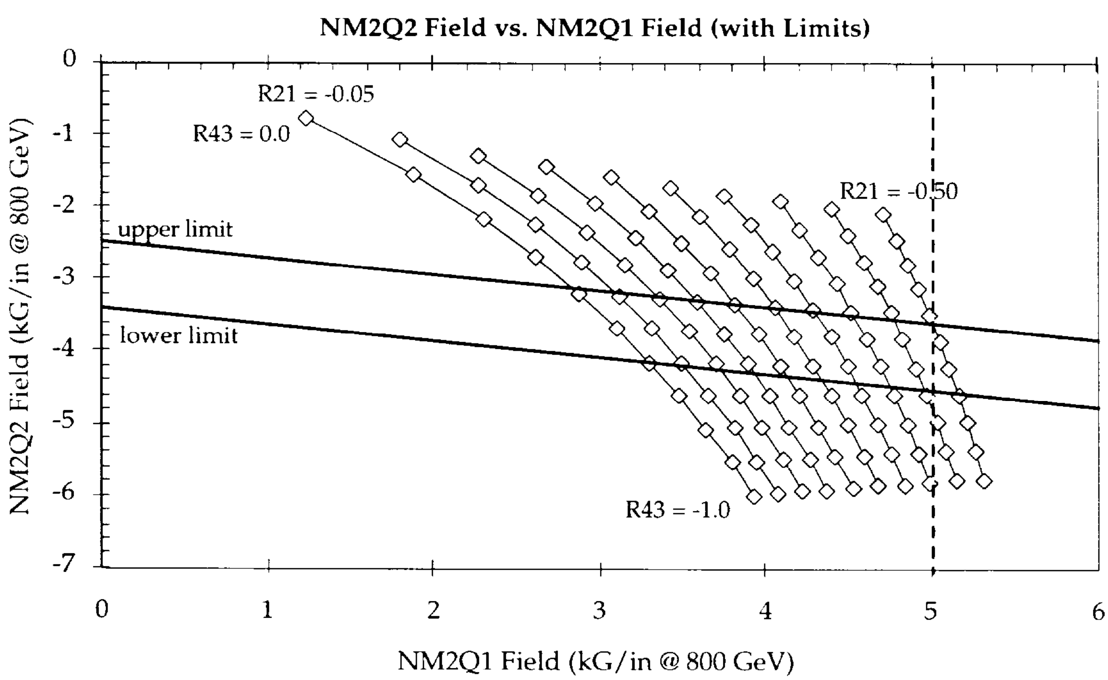


Figure A3.5: NM2Q2 Field vs. NM2Q1 Field (with Limits). Diagonal lines show limits at $0.217*I_{NM2Q1} + I_{NM2Q2} = -2.95 \pm 0.45$ kG/in @ 800 GeV (-567 ± 86 amps). The dashed line is the current limit on NM2Q1 at 5.0 kG/in @ 800 GeV (1011 amps). The R_{21} and R_{43} values shown are in mrad/cm.

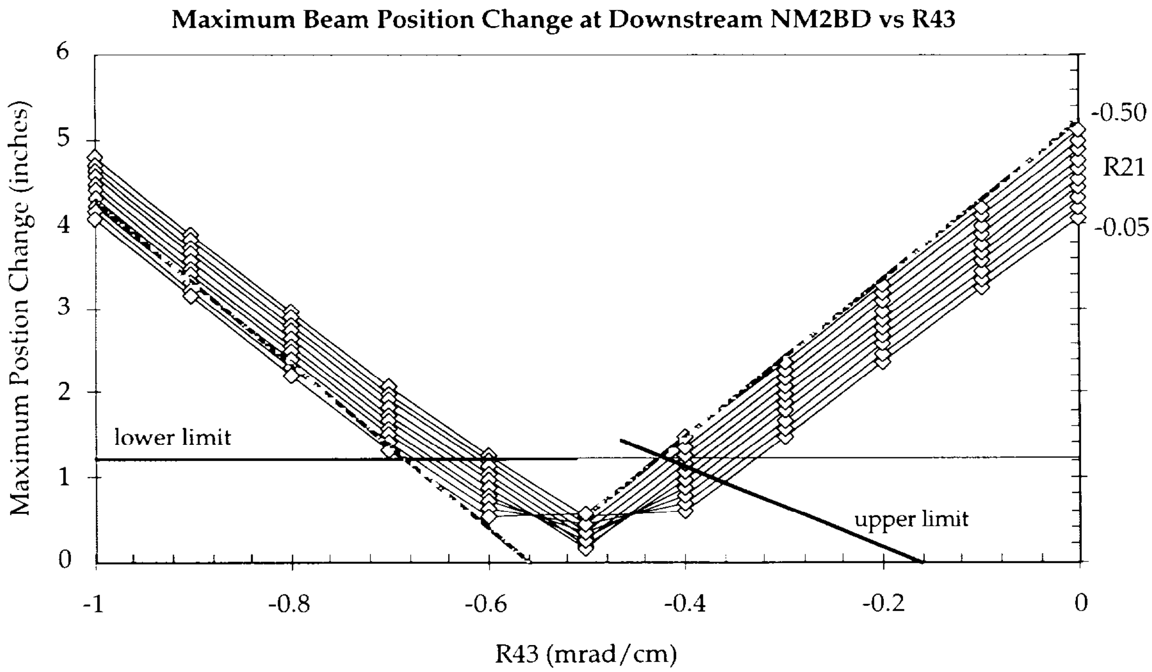


Figure A3.6: Maximum Beam Position Change at Downstream of NM2 Beam Dump vs. R_{43}. The 1.23" line signifies the farthest upward position change that a primary proton beam can travel and still impact on the Beam Dump. The upper and lower limits correspond to the limits on Figure A3.5, and the dashed line corresponds to the dashed line on Figure A3.5, showing the current limit on NM2Q1. The R_{21} values shown are in mrad/cm.