The Precise Alignment of the Fermilab KTeV Experiment

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ABSTRACT

The two new neutral kaon CP violation experiments currently running at Fermilab, collectively known as KTeV, use a common beam and detection system. The need for accurate primary beam targeting and precise neutral beam definition have led to stringent alignment tolerances. The alignment must insure that a 0.25 mm size (σ) primary beam hits the target and is stable to better than ±0.1 mm, that the target-collimator system which forms the secondary neutral beams be positioned at the 0.25 mm level, and the two resulting beams have equal size and momentum spectra. Results so far indicate that all expectations have been met. The primary beam hit the target on the first pulse. Preliminary off-line analysis shows the target-collimator system was aligned to better than 0.25 mm horizontally and 0.5 mm vertically, and that stability was within 0.1 mm for periods of months. This paper gives an overview of the methods, the implementation, and the results of the precise alignment of the KTeV experiment. We also discuss stability issues and the current status of the experiment's alignment monitoring system.

1. INTRODUCTION

Using two carefully matched neutral kaon beams, KTeV is currently making very high precision physics measurements addressing the origins of CP violation, and is doing very sensitive searches for rare and forbidden kaon decays. Precision alignment plays a fundamental role in the success of the KTeV physics program by contributing to the reduction of possible systematic errors below the sensitivity noise level.

1.1 Experiment overview. Design parameters.

KTeV currently consists of two experiments: E799-II and E832. E799-II is a search and/or study of neutral kaon and hyperon rare decays. E832 is a high accuracy measurement of ε'/ε at the10^{-4} level. The secondary beams are two neutral horizontally separated square beams. In E832 a regenerator alternates between the beams every spill. The regenerator beam is used to re-create K^0_S from an almost pure K^0_L beam [1].

The experiment and associated beam lines are underground in two essentially isolated enclosures, as shown in Figure 1. The primary beam, the target, and part of secondary neutral beam are contained in one enclosure (NM2). Subsequent components of the neutral beam and the experiment are contained in a pair of contiguous newly built enclosures (NM3/4). Beam transport between enclosures NM2 and NM3 is made possible through a buried beam pipe.

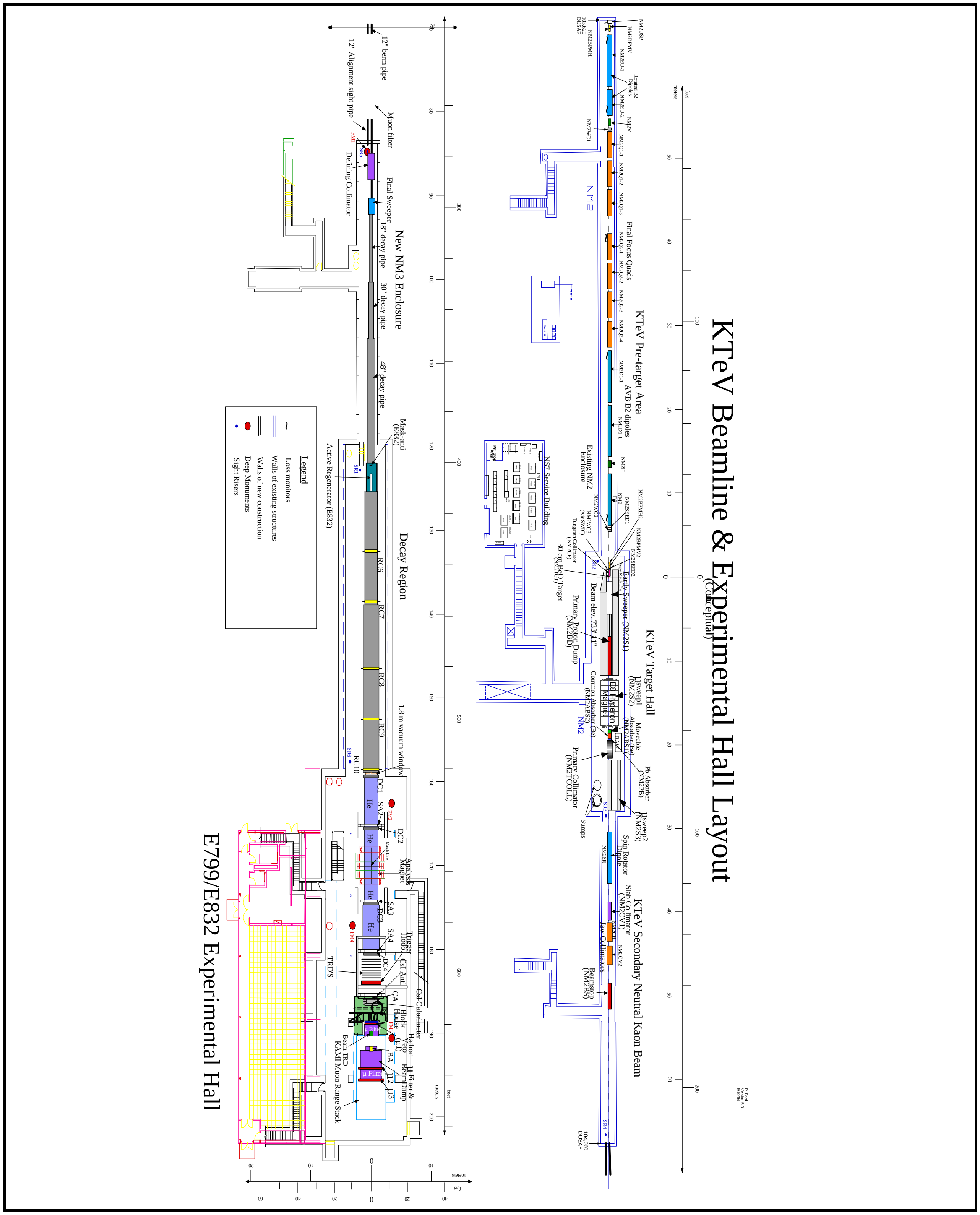

Figure 1. KTeV Experiment Layout

Additionally, a regular 0.30 m diameter horizontal sight pipe has been installed for providing direct visibility between enclosures for alignment purposes.

Table 1. Primary Beam Specification

Proton beam energy	800 GeV
Proton intensity	5 x 10^{12} protons per 20 sec spill
Length of run	1 year
Targeting angle	-4.8 mrad (vertical) <0.02 mrad (horizontal)
Targeting angle variability	-4.0 mrad to -5.6 mrad (vertical)
Beam size at the target (σ)	≤ 250 μm (horizontal and vertical)
Beam spot stability	≤ ± 50 μm (horizontal and vertical)
Beam position stability	≤ ± 100 μm (horizontal and vertical)
Beam angle stability	≤ ± 25 μrad (horizontal and vertical)

The experiment requirements for the symmetry and alignment of the two neutral beams were quite challenging. Not only did the collimators which formed the secondary beam have to be both machined and aligned precisely, but the location, shape, and targeting angle of the primary beam needed to be well known and controlled in order to reduce possible systematic errors to a negligible level. The requirements for the primary beam are listed in Table 1.

1.2 **Tolerances for alignment and beam stability**

The primary beam is transported from the extracted beam system to the KTeV target through a long string of components. It is essential that the beam (0.25 mm σ size) impinge accurately on the target and must be stable. Though the exact value of the vertical targeting angle is not as critical as the horizontal, it must be stable. The horizontal targeting angle must be very nearly zero in order to keep the intensities and energy spectra of the two beams equal.

The secondary beam starts with the target. Driven by the physics requirements, the need for precise alignment of the neutral beam derives from the necessity for clean and very well defined beams. Each beam must be well contained (no halo outside the defined beam area) in order that excessive physics backgrounds not be generated, and the CsI calorimeter not be damaged by radiation. Figures 2 and 3 show a plane and respectively a 3-D view of the E799-II detector configuration. Two criteria imposed the horizontal and vertical positioning tolerance:

- the secondary beam size and position at the CsI Calorimeter (186 m from target) should be affected no more than 0.5 mm from the sizes and alignment of various collimator apertures;
- the areas of the two beams must be equal to within 1% [2].

The definition of the secondary beams depends on the precise alignment of the beam-target-collimator system. They are required to be aligned to ±0.25 mm relative accuracy.

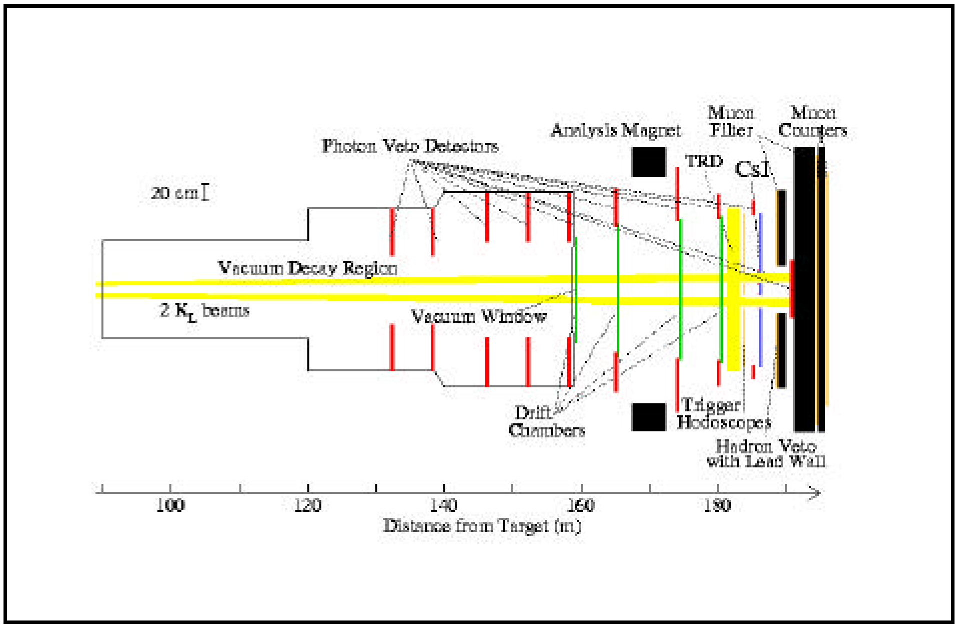

Figure 2. Plan view of KTeV E799-II detector configuration

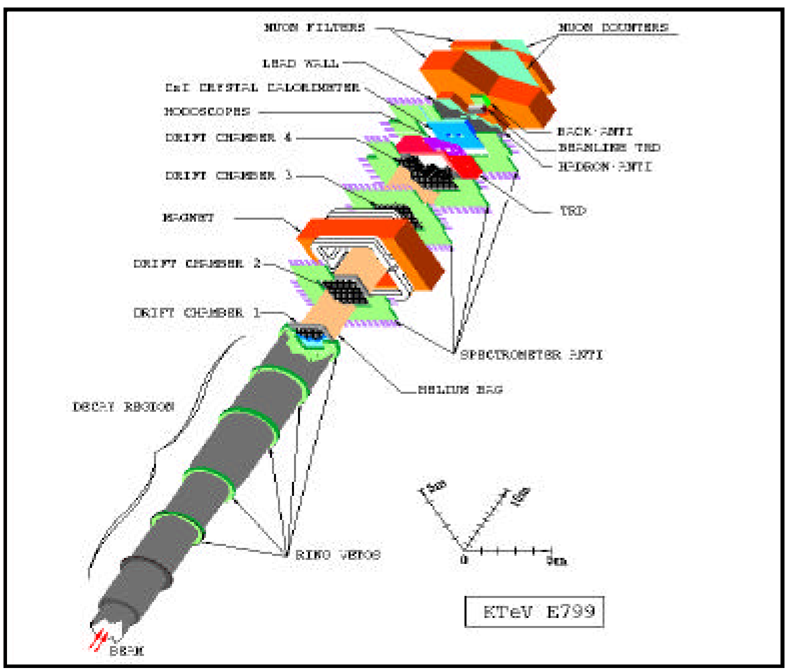

Figure 3. 3-D view of KTeV E799-II detector configuration

2. ALIGNMENT CONCEPT AND DESIGN

The design phase played a crucial role in the successful alignment of the experiment. Starting from the complete understanding of KTeV's requirements and ending with details about the alignment and monitoring of each component, a very comprehensive plan was formulated in preparation for the installation of the experiment. The alignment and stability concepts have been incorporated in the "KTeV Beam Systems Design Report" [2].

Design and planning for the installation and alignment of the experiment was critical. During the design phase, the Survey-Alignment-Geodesy Group has been actively involved with the KTeV collaboration in important areas. A number of issues were addressed:

- determination of the required positioning tolerances between the theoretically desirable and practically achievable;
- early and active participation and support of the SAG group in the design of the components to ensure that the systems can be realistically aligned to required tolerances with a cost-effective effort on the part of the alignment teams;
- understanding of the position stability as might be affected by such factors as ground motion and thermal stability.

The alignment concept for the installation and position monitoring of the KTeV experiment is discussed below.

2.1 Surface geodetic control network

The experiment is constructed in the Fermilab site (accelerator) coordinate system. For historical reasons, this local reference system is referred to as the DUSAF system. For absolute positioning, the horizontal accuracy of the DUSAF system is ±3 mm. Though adequate for the civil construction and to relate KTeV to the extracted beam system where the primary beam is initially defined, it is not accurate enough for final focusing, targeting, and neutral beam alignment. Therefore, a local KTeV Surface Control Network was developed. In this Surface Control Network, the horizontal and vertical aspects have been treated separately. The vertical control network is carried out through the existing Fermilab vertical reference frame.

The design and optimization of the Surface Horizontal Control Network led to a configuration of polygons with central points and chain of quadrilaterals to ensure a strong geometric figure. The network consists of a combination of ten survey monuments, placed outside the project construction area, and six vertical sight pipes for transferring coordinates. This network is used to tie NM2 and NM3/4 together, and its geometric configuration is shown in Figure 4. The Surface Horizontal Control Network was designed to be observed using both conventional and Global Positioning System (GPS) techniques and tied to the DUSAF system. Pre-analysis and simulations indicated that absolute error ellipses in the ±0.6 mm range should be obtained. Therefore the Surface Horizontal Control Network is consistent with DUSAF datum, but is locally about five times more accurate than DUSAF. Its accuracy is sufficient not only for strengthening the azimuth constraints and establishing a more precise scale for the underground network through the points transferred from outside, but also for construction and experiment monitoring purposes.

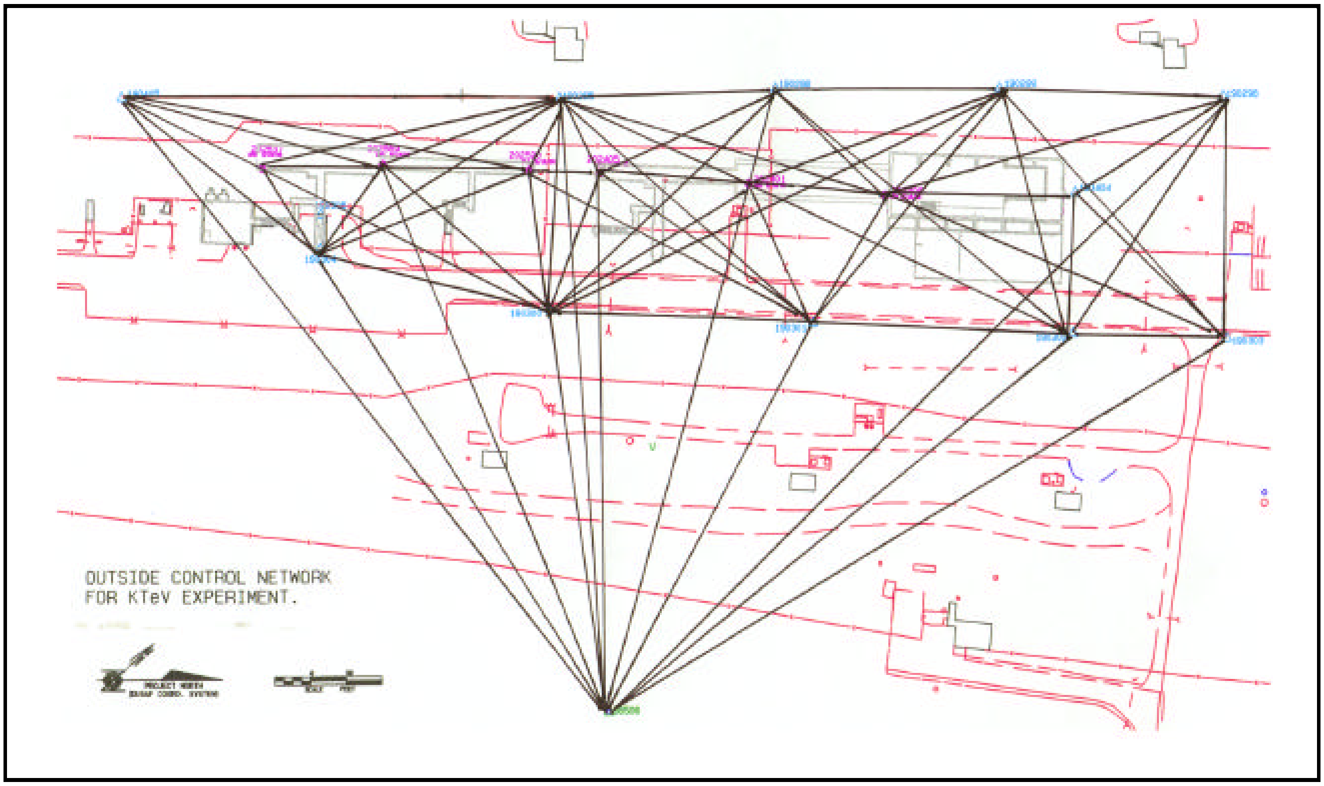

Figure 4. KTeV Surface Horizontal Control Network Phase II.

The Surface Horizontal Control Network was implemented in two phases. As initial implementation, it was used by the civil construction contractor to layout the buildings and by theSAG group for quality control checks of the layout work and monitoring the construction. The second phase, after construction, necessitated another high precision survey of the network for incorporating the six vertical shafts and transferring surface coordinates to the KTeV Underground Control Network.

2.2 High accuracy underground control network

KTeV is mainly sensitive to the final primary beam trajectory and to the neutral beam geometry, therefore a major requirement for the experiment's alignment is to minimize the relative errors. This calls for a high accuracy underground control network with very strict and tight tolerances, which makes it possible to establish relative component positions to ±0.25 mm (2σ) throughout the experiment. It is also the basis for a dynamic monitoring system for relative position checks on components.

The accuracy of the network can only be understood through an in depth knowledge of the stochastic behavior of that network. In order to develop an adequate underground network and to formulate its mathematical models, various criteria such as accuracy, reliability and expense needed to be balanced. Such an optimization process has been carried out in the design phase of the network, comprising the same four design orders employed in classical geodesy in relation to:

- the optimal reference system,
- the configuration of the network and observations plan,
- the search for an optimal distribution and observation weighting, and
- the improvement the isotropy and homogeneity of the network by including additional points and/or observations.

The configuration of the network is limited by the shape and the geometry of the enclosures and the Experiment Hall which dictates that the KTeV underground network be of longitudinal type. The studies carried out led to a framework system based on chains of polygons with central points throughout the NM2 and NM3 enclosures, and the Experimental Hall. To improve the isotropy of the network and compensate the weaknesses caused by the poor ratio between some sides of polygons, additional measurements spanning adjacent polygons were added. Redundant observations were needed to ensure quality and uniformity of accuracy. Figure 5 shows the planar configuration of the precise underground network in the Experiment Hall.

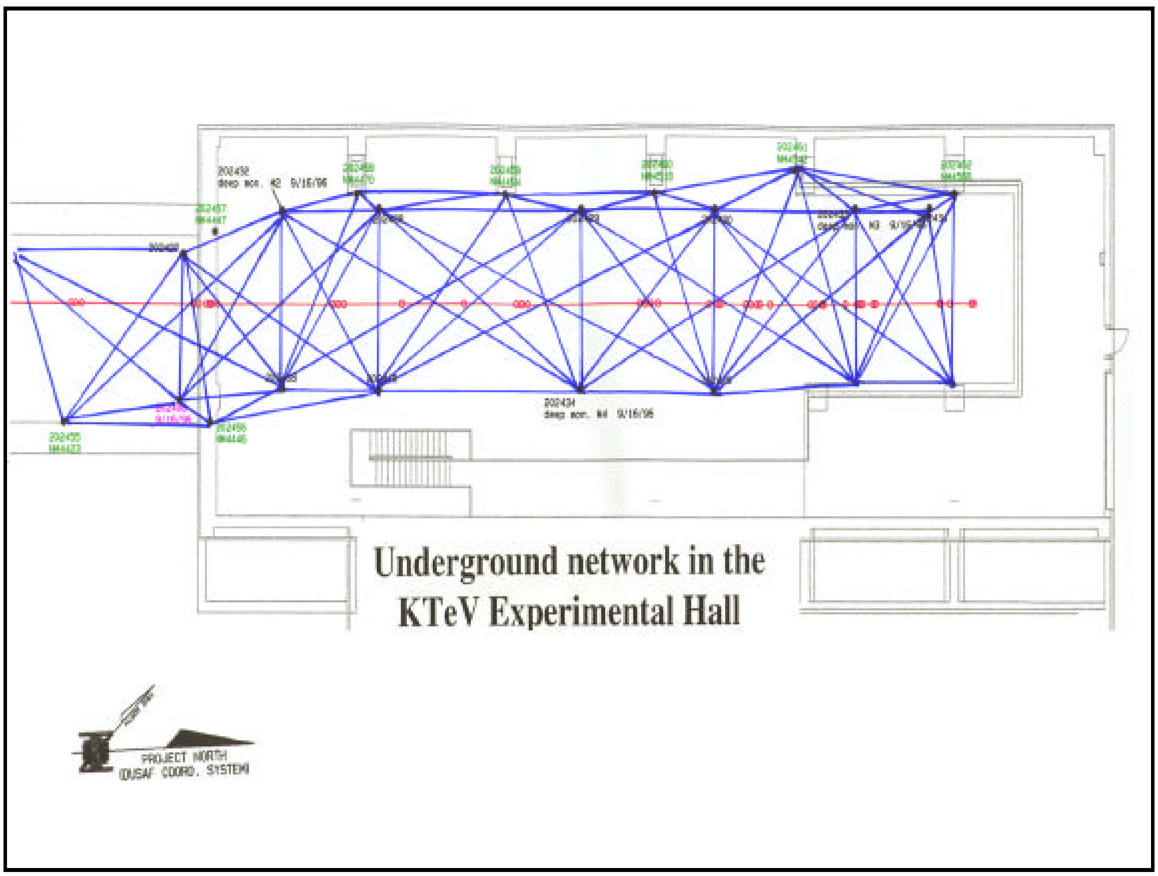

Figure 5. KTeV Underground Control Network in the Experiment Hall (NM4**)**

The underground reference control system is defined with respect to monuments permanently imbedded in the enclosure floor, alternating with monuments rigidly attached to walls for improving the overall spatial geometry of the network. Because the Laser Tracker was chosen for observing the network, the actual monuments are implemented using high-precision socket type holders to support spherical reflectors whose centers define the monument coordinates in all three dimensions. This control network consists of 140 monuments, the positions of which must satisfy a number of criteria:

- the points must be easily accessible;
- minimize the number of observations necessary for component positioning and to allow for eventual smoothing routines;
- the density of the points has to be great enough to cover the objects to be surveyed; and
- the network structure must be flexible enough for future needs.

The points of this control network are fixed and used as the basis for component alignment.

Network simulations and pre-analyses of different models led to the design of an optimum number and location of six vertical sight risers used for transferring coordinates from the Surface Control Network. These points provide azimuth constraints, concurrently controlling the scale of the network.

Tying the control points between the two enclosures by direct observations through the horizontal sight pipe and the beam pipe requires a special procedure involving simultaneous observations with two Laser Tracker instruments and a carefully controlled environment. The horizontal sight pipe also provides a direct access for checking the relative accuracy between critical components , such as the collimators, in NM2 and NM3/4 at any time.

The underground network is processed as a three-dimensional trilateration network, with distances computed from the Laser Tracker observations. Error propagation analysis indicates that this network should achieve a relative accuracy between control points at the target and the end of the experiment hall (~ 200 m) to better than ±0.3 mm at 95% confidence level.

The vertical reference frame for the underground control is carried out from the surface monuments through the sight risers, and uses precise leveling through the tie-rods permanently mounted into the walls of the enclosures and Experiment Hall. Relative orthometric heights between any two points of the experiment can be determined within ±0.25 mm at 95% confidence level employing standard procedures and controlling the environment.

2.3 Components fiducialization and installation

Fiducialization of the components relates their effective beam centerlines to external mechanical points that are accessible for subsequent survey measurements. Since the KTeV beamline and experiment consists of many different types of hardware, requiring different alignment tolerances, a specific fiducialization and installation procedure has been developed for each element or class of elements. These procedures have been included in the comprehensive alignment plan presented in the design report document [2].

The following are general criteria which must be considered during fiducialization. The critical parameters must be available in six degrees of freedom to the survey crew. 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. 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 for geometry purposes. The following procedure has been developed to insure that each beam or detector element be properly fiducialized and aligned:

- Each KTeV system manager provides specific alignment tolerances and specifications;
- The system manager submits engineering drawings which show fiducial points and alignment adjustments for review and comments. This is an iterative process. For critical tolerance elements the alignment project manager should be involved from the beginning. If there is a proposal to independently fiducialize a beam or detector element, the methodology must be reviewed by the Fermilab SAG group;
- Once a plan is in place, any hardware (such as sphere mounts, tooling balls, or targets) necessary for the fabrication process is distributed by the alignment group;
- The system manager provides a tentative schedule indicating when the beamline element or detector will be ready to be fiducialized, installed, and aligned;
- When arrival of the detector or beam element is imminent, The KTeV installation coordinator schedules a time and place for the above with the alignment group; and
- Results of each survey and alignment are analyzed by the SAG group and provided to the appropriate subsystem managers.

While the Laser Tracker has been chosen as the primary alignment tool for providing greater accuracy and also reducing the time necessary for component alignment, optical tooling techniques will be extensively used for rough alignment.

2.4 Smoothing and final alignment

The initial installation of components process satisfies the absolute positioning aspect by relating the designed beam system coordinates to the coordinates of the supporting control points. It is important to note that the most stringent tolerances for KTeV involve the relative positioning of the components, especially the alignment of the beam-target-collimator system to ±0.25 mm relative accuracy.

As the final step in the alignment of the experiment, a smoothing procedure has been developed. Starting with the “as set” coordinates of the beamline and experiment components, a weighted linear fit, separately for the horizontal and vertical planes, is computed. The weighting factor for each component is a function of its designed alignment tolerance. The highest weights are assigned to the target, the two collimators, and the CsI Calorimeter. The pre-target components are given similar weights because the incoming beam trajectory through the target defines the initial secondary beam trajectory. This way, the incoming primary beam is forced to be collinear (coincide) with the secondary beam, and fulfill at the same time the neutral beam requirements. Each component is moved, if necessary, only by the value of the residual at that place. The detailed analysis of underground network is correlated with the results of the smoothing which is based on the RMS sum of the component residuals. This gives us information about the quality of the alignment.

2.5 Monitoring relative positions and stability

Maintenance of the underground control network and monitoring of relative component positioning are required since all the survey and alignment tasks analyzed pertain to a static situation. After initial determination of the horizontal and vertical control networks, the SAG group implements a regular schedule for re-measurement of these networks and conducting detailed analysis, including robustness estimators in modeling the data, for detection of displacements or deformations.

In order to provide better stability monitoring for the underground networks, four permanent deep monuments have been built in the NM3 enclosure and Experiment Hall. Besides providing stable monitoring references closer to the experiment, these monuments also constitute fundamental references for the underground control by reducing the amount of time it takes to reestablish the network inside the KTeV hall. The four monuments are isolated from the slab and deep enough to sharply reduce the effects of weather and building settlement. A deformable material, bentonite, has been used between the outside casing and the monument pillar to prevent motion due to lateral soil pressure.

Monitoring alignment of the neutral beam elements to the required tolerances is critical for the KTeV program. The primary beam also must be stable on target. If the locations of elements are not stable within the specified accuracy, they must be corrected quickly. 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. Since the most stringent alignment requirements are relative positions, an on-line dynamic monitoring system is employed. A part of the plan for monitoring the KTeV geometry includes the use of tiltmeters and a Hydrostatic Leveling System (HLS). As instrumentation, we employed KERN Swiss NIVEL 20 Tiltmeters that register in two orthogonal directions with a resolution of 0.001 mrad, and the HLS (FOGALE Nanotech system). Mounted on a number of critical devices, these systems provide information independent of beam data.

3. ALIGNMENT AND STABILITY RESULTS

3.1 Alignment results

The Horizontal Surface Control Network has been carried out employing Kern Mekometer ME5000, Kern E2 theodolites, and Trimble 4000SSE Geodetic Survey GPS receivers as instrumentation. After the completion of the NM3/4 enclosures construction, the network has been re-observed for determining the coordinates of the underground transfer points. Figure 6 shows a histogram of the standardized observation residuals. The 95% confidence level absolute error ellipses obtained for all the control points in both surveys were in the ±0.6 mm range. Wild NL plummets with 1/200000 accuracy have been utilized for transferring coordinates from the precise surface network in enclosures.

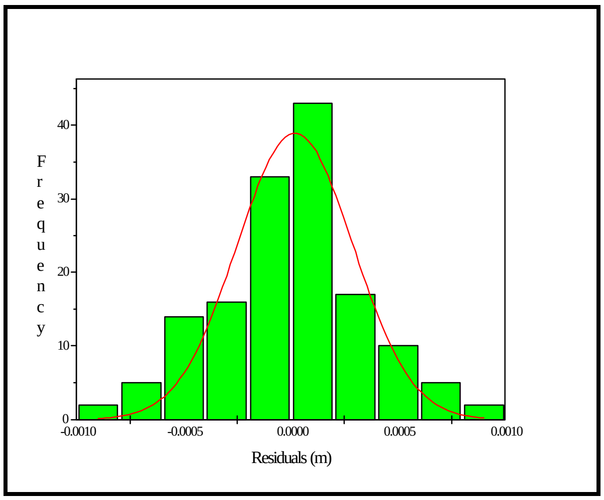

Figure 6. Surface control network.
Histogram of standardized observation residuals.

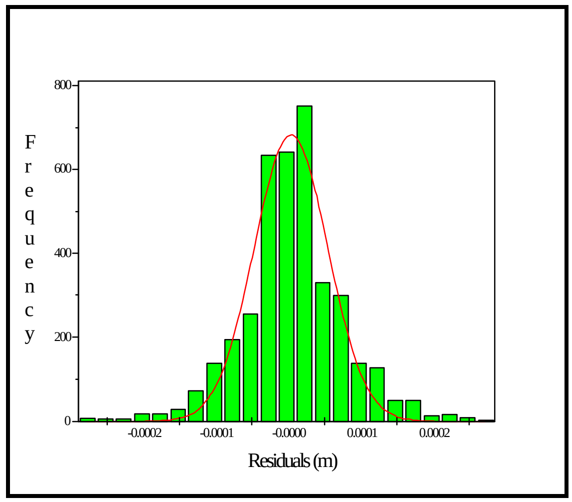

Figure 7. Underground control network.
Histogram of standardized observation residuals.

The Underground Control Network has been measured exclusively with the Laser Tracker. It has been processed as a three dimensional trilateration network. Between 1995-97 the network has been re-measured four times for maintenance and monitoring purposes. Figure 7 shows the standardized observation residuals distribution for the latest underground network.

We obtained relative errors between control points from the target area and, throughout the network, to the end of the experiment consistently below ±0.35 mm, at 95% confidence level, as shown in Figure 8. The vertical reference network has been also re-measured six times using Wild N3 and NA3000 levels. In each surveying campaign precision in the range of ±0.6-0.8 mm/km double run has been obtained. All the beam and detector components have been fiducialized by Fermilab. The Laser Tracker, optical tooling, Coordinate Measuring Machines, or a combination of them have been utilized for fiducialization. All beam and detector components were installed and aligned using the Laser Tracker and optical tooling.

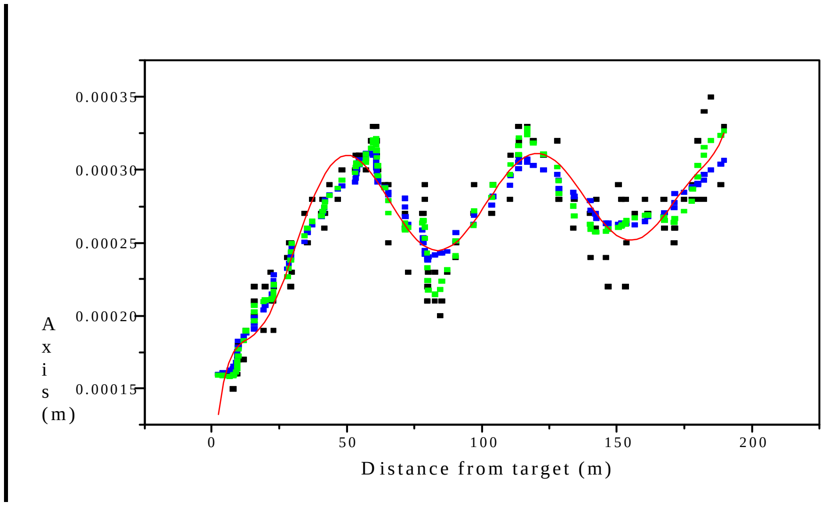

Figure 8. Underground control network.
Semi-major axis of relative ellipses of errors (95%) related to the target.

During the last measurement of the underground control network, simultaneous observations of all beam and experiment components have been performed with the Laser Tracker. These measurements provided the data for computing the "as set" coordinates of the beamline and detector components. According to the designed smoothing procedure, a weighted linear fit has been computed separately or the horizontal and vertical planes. The results of the fit indicated that the critical components defining the final trajectory of the primary beam on the target and the trajectory of the secondary neutral beam, satisfied the ±0.25 mm relative positioning requirements. All the other beam and detector components have also been found to conform to the required tolerances. Figure 9 shows component residuals to the weighted linear regression computed in the horizontal plane. As a result, no smoothing correction was necessary.

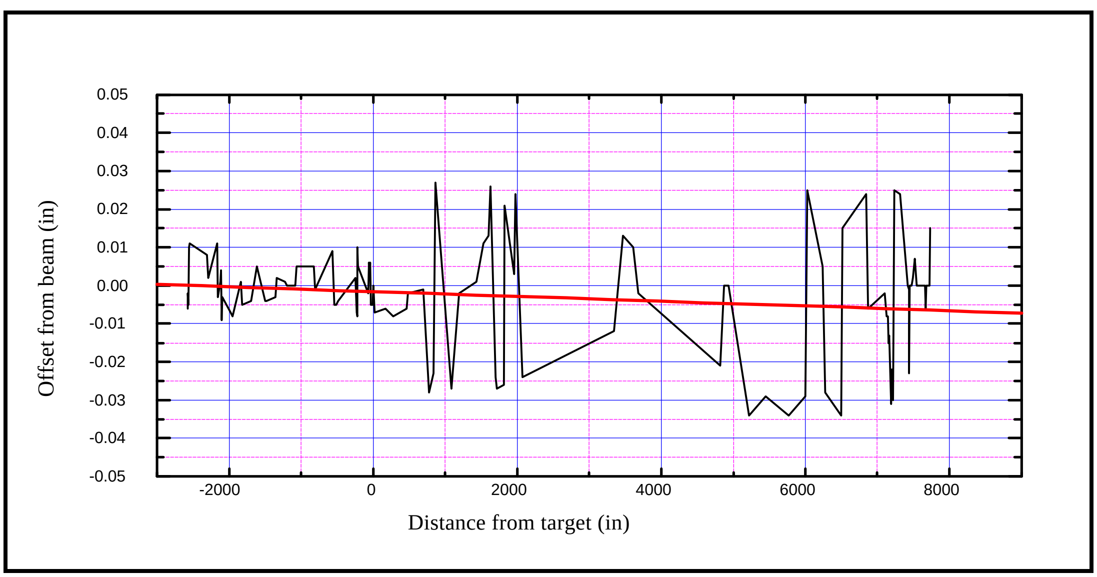

Figure 9. Smoothing in the horizontal plane:
Weighted linear regression through the installed components.

As a final step, the complete analysis of the spatial geometry of all experiment components in relation to the beam has been performed. The experimenters have been provided with summary files containing detailed information about the offsets and rotations of each component with respect to the beam for use in their analysis software.

3.2 Error budget analysis

Mathematical and statistic analysis has been performed to define the total error budget for the Laser Tracker alignment of the KTeV experiment components, and also to determine the contribution of each individual error to the model, based on the differential and variational influence principle. A summary of the major component errors at one σ is the following:

$$\sigma = \sqrt{\sigma_n^2 + \sigma_m^2 + \sigma_f^2 + \sigma_s^2} = \sqrt{0.143^2 + 0.072^2 + 0.070^2 + 0.050^2} = \pm 0.182 \text{ mm},$$

where:

- σ_n relative errors in the network;
- σ_m control points to fiducials;
- σ_f fiducials to component center; and
- σ_s resolution of the adjustment device.

3.3 Beam commissioning results

The results of the alignment effort were demonstrably successful. Two measurements or observations show the level of success.

First, the primary beam, when first turned on, hit the target to an accuracy consistent with the magnet tolerances. This was an exceptional occurrence! Figure 10 shows horizontal and respective vertical beam profiles at the target. The bringing of the beam onto the target depends on the absolute relationship of the KTeV grid to the site grid, and then on the detailed relative locations of magnets and target assembly within the KTeV system in the NM1 - NM2 enclosures.

Second, the locations of the two beams at the CsI Calorimeter, as measured by reconstructed K long decays into three neutral pions, were accurate (centered) to better than a millimeter. Figure 11 shows horizontal and respective vertical profiles of the neutral beam at the CsI detector. The histogram represents observed beam data and the dotted graph represents the ideal position and shape of the beam generated by Monte Carlo simulation. The units of the horizontal axis are mm. Not only the positioning, but also the rectangular shape without tails represent a major improvement over previous neutral beam collimation systems at Fermilab fixed target experiments. This success depended on the precise alignment of the target-collimator-CsI Calorimeter systems, respective in the enclosures NM2 - NM3 - NM4.

3.4 Beam stability monitoring systems

The alignment and stability were checked using a variety of methods including re-measurement with the Laser Tracker, on-line and off-line analysis of beam and physics data, and independent hardware designed to monitor relative motion.

Primary beam stability was monitored with a pair of SEEDs, which are essentially high resolution wire SEMs with 125 μm and respectively 250 μm wire spacing, just upstream of the target. SEED profiles at the target are shown in Figure 10.

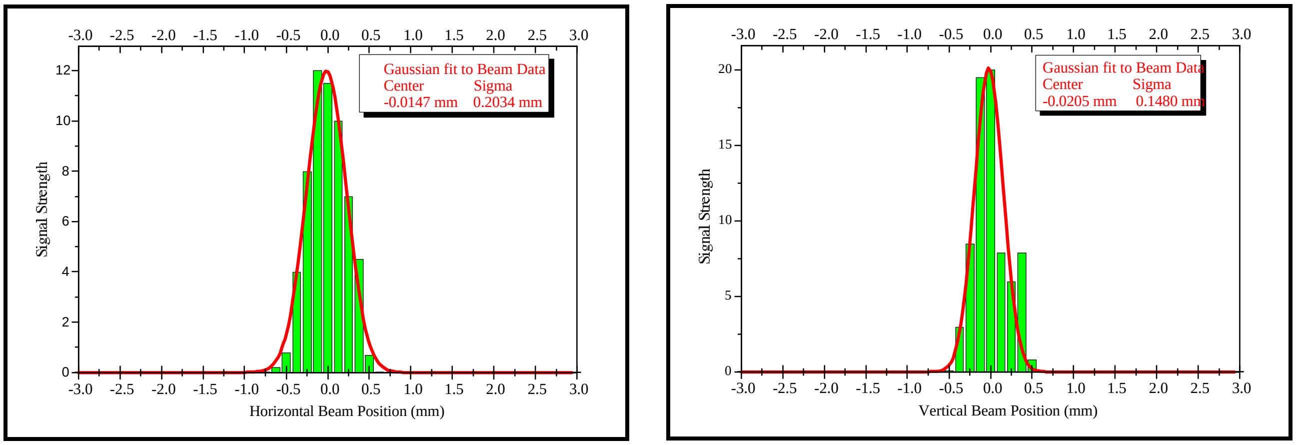

Figure 10. Horizontal and Vertical Beam Profiles at the Target

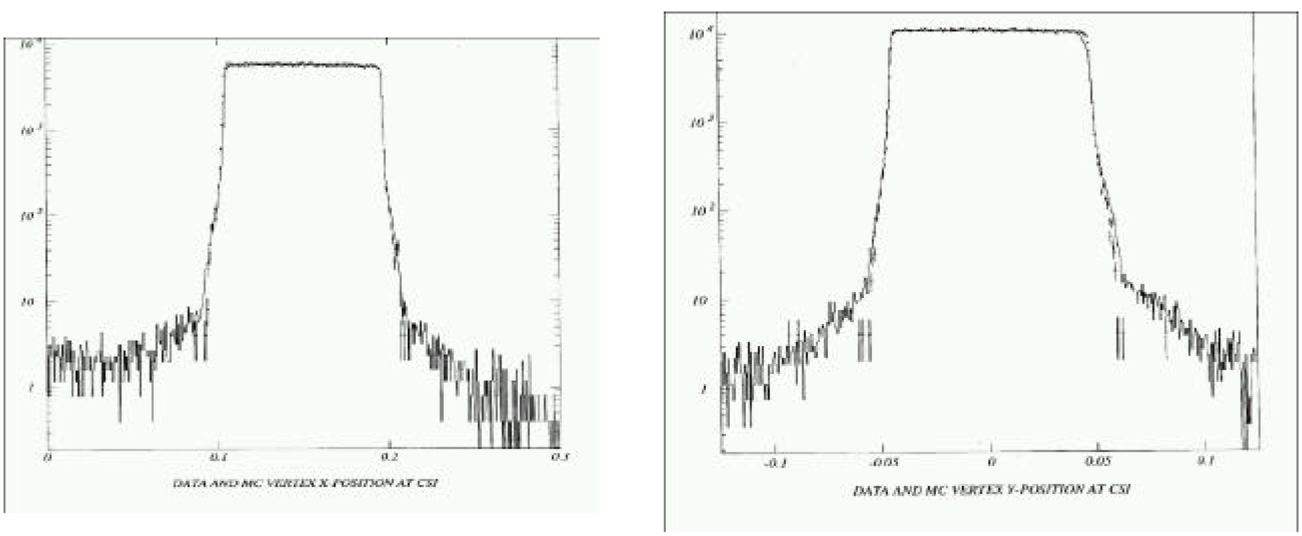

Figure 11. Horizontal and vertical profiles of the neutral beam at the CsI detector.

The histogram is observed data and the dotted graph is the ideal position and shape generated by Monte Carlo simulation
(horizontal axis units are in meters).

Results indicate that we monitored the stability of the beam with a resolution of less than 10 μm. Secondary neutral beam stability (target-collimator-CsI system) was monitored by reconstructing K^0 decays using the KTeV detector as shown in Figure 11. The on-line technique during data taking monitored positions to about 1 mm. Off-line after complete detector calibration we should be able to determine positions at the level of our design goal (200 μm). These results are still preliminary and the detailed analysis continues.

The tiltmeters and HLS probes were mounted on a number of critical devices. The analysis of the data from these stability monitoring systems is also still in progress, and the results presented here are still preliminary. It was not possible to monitor the target system with the tiltmeters due to excessive radiation. The upstream collimator was monitored, but two tiltmeters failed from radiation exposure. Because of software problems, the tiltmeters were not logged as part of the KTeV data acquisition system, but were monitored periodically on a manual bases. Longer term monitoring of the Defining Collimator, the Spectrometer Magnet and the CsI Calorimeter was effective. Figure 12 shows the Spectrometer Magnet rotations and stability monitored over a nine month period. The tiltmeter data indicated that the magnet was stable to an accuracy of about 20 μrad.

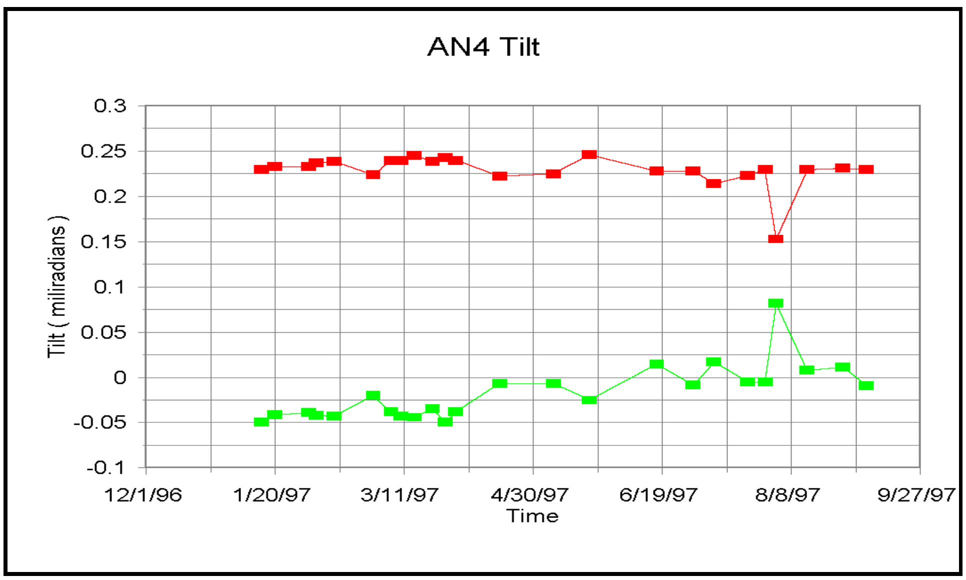

Figure 12. Lateral and longitudinal rotations of the Spectrometer Magnet monitored with the Tiltmeter.

The HLS system was initially planned to extend from the target area to the CsI Calorimeter. Again, due to radiation levels, and also due to large temperature variations in the Target Hall compared to the Experiment Hall (relative variations of order 20^0 C), it was not possible to monitor the entire system. The system that was monitored for the last four months of the experiment consisted again of the Defining Collimator, the Spectrometer Magnet. Data from the HLS system was read into the KTeV DAQ system.

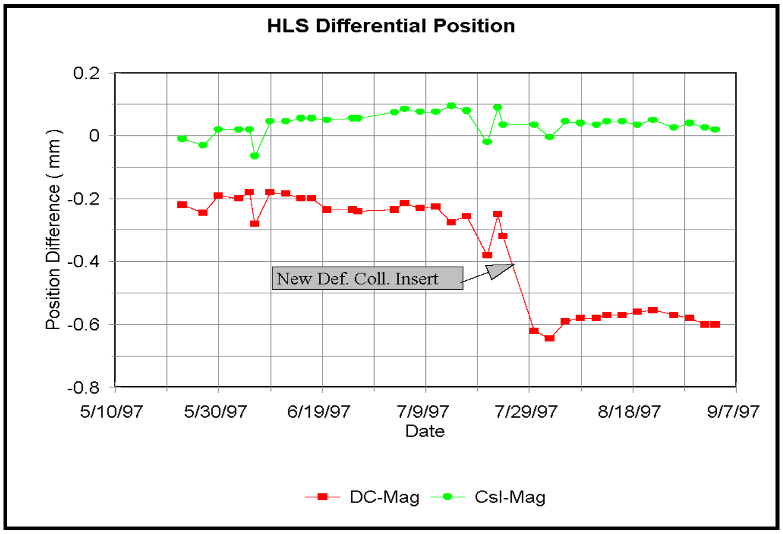

Figure 13. Vertical position of the CsI detector and Defining Collimator referred to the Spectrometer Magnet.

In this long term stability analysis, the Spectrometer Magnet is used as reference. Figure 13 shows the differential vertical position of the Defining Collimator and the CsI Calorimeter over the four months period. While some small shifts in the angle of the CsI were observed, the relative height of the CsI Calorimeter with respect to the Spectrometer Magnet remained constant to within about 100 µm over this period. The Defining Collimator was subject to systematic shifts during changeover of experiments, but during periods of running of a single experiment (2-3 months) the collimator was also stable to about 100 µm relative to the Spectrometer Magnet.

The HLS readout on individual items was subject to apparent shifts of a couple millimeters due to thermostatic fluctuations. Figure 14 shows such a systematic progressive shift exceeding 0.25 mm in the raw HLS data sample collected continuously over a 250 minutes period for analyzing short term stability. However, as shown in Figure 15, differential shifts were very small, in the 10 µm range. Note that for the vertical axis of Figures 14 and 15, the conversion factor from Volts to linear units is: 0.1 Volt = 50 µm.

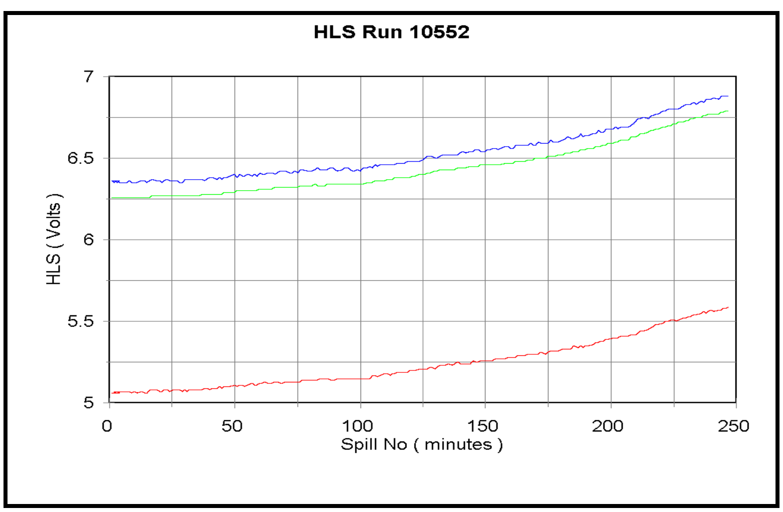

Figure 14. Raw HLS data of the CsI Calorimeter, Defining Collimator, and Spectrometer Magnet stability monitoring. (Vertical scale: 0.1Volt = 50 µm)

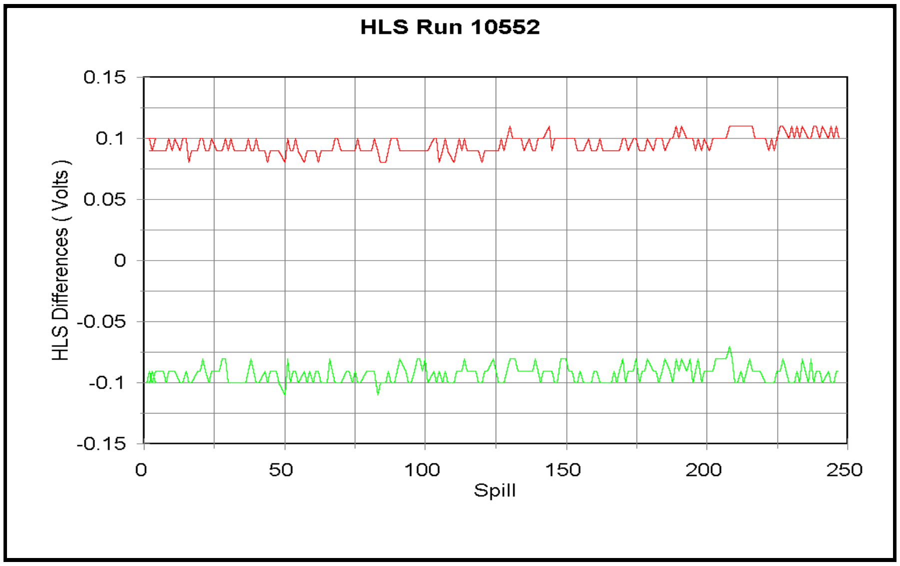

Figure 15. Stability of the CsI Calorimeter and
Defining Collimator referred to the Spectrometer Magnet over time.
(Vertical scale: 0.1Volt = 50 μm)

4. CONCLUSION

The network to support the installation and commissioning of the KTeV experiment was, as demonstrated by the initial accuracy of the positions of the primary and the neutral beam with respect to the experiment a success. Long term monitoring based on multiple re-surveys and instrumentation monitoring, though still being analyzed, indicates that the geometry of the experiment was very stable. These results represent a major improvement compared to other similar experiments.

5. ACKNOWLEDGMENTS

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