SPEAR3 Alignment Chapter

For Nuclear Instrumentation and Methods in Physics Research, Section A
June 25, 2004

Catherine Le Cocq, Brian Fuss
Stanford Linear Accelerator Center, Stanford, CA, USA

1. INTRODUCTION

The alignment of SPEAR3 had a unique challenge in that a critical criterion was to recreate the position of the orbital beam path of SPEAR2 in the new ring so that some existing tangential beamlines could be preserved. Overall the goal was to position newly manufactured and fiducialized magnets and vacuum chambers in the ring but also to survey a newly poured and very flat concrete floor. In the following discussion these tasks will be presented as a two-step process: First the existing SPEAR2 ring and surrounding areas had to be resurveyed and critical monumentation that would be lost had to be compensated for. Second, as soon as the new floor and other construction changes were complete, new monumentation had to be installed and then used in the task of placing and aligning the new SPEAR3 components. The result was that everything was aligned correctly and beam was circulated without any alignment changes.

2. Preparation with the SPEAR2 Ring

Placing new magnets and other components into the new SPEAR3 ring so that the beam orbital path will match the existing SPEAR2 path was critical to the success of the project. SPEAR2 was originally built using only optical tooling techniques without a rigorous three-dimensional survey network. Over the years since SPEAR2 was completed various new surveys and networks were completed but only for certain limited areas of the ring.

The first task necessary to establish a baseline reference to the existing ring was to gather and combine all available existing networks and adjust them together mathematically in a free datum solution. It was decided to use a Free Network Adjustment approach as well as a Minimal Constrained Solution. Data from a September 2001 booster ring survey, a March 2002 BTS (Booster-to-SPEAR) survey, a building 130 survey and other ring surveys completed as late as February 2003 were combined into a network of 330 points. The Free Network approach combined all the data giving new coordinate positions similar to the old coordinates to much less than a millimeter. This ensures that all these unique datums are in fact compatible and allow the Minimal Constrained solution to give a good new set of network coordinates.

The network was constrained in position and orientation by mathematically fixing one southern monument in one direction and fixing another northern monument in all directions. New leveling data was included in this. One goal was to tie SPEAR into the rest of SLAC's coordinate system through the use of existing SLAC monuments associated with End Station A.

Another opportunity was to revise the SPEAR2 component nomenclature for SPEAR3 so that the numbering scheme would have a clockwise direction which is the same as the electron beam direction.

Thus SPEAR3 has a new orientation with the origin still at the center of the ring but with positive X being in the general direction of the booster ring. Coordinate biases were also revised so that the Z offset is now 6000 meters, the X offset is 3000 meters, and the Y offset is 500 meters. The height of the ring origin has been established as 75.7912 meters above sea level. Along with these changes existing SPEAR2 wall monuments that were expected to remain for SPEAR3 were also renamed to match this new network of survey reference points.

3. Fiducialization

The magnets and other components to be installed into SPEAR3 were newly built. Over two hundred new magnets and 60 new vacuum chambers plus other specialized equipment had to be fiducialized or checked with the laser tracker before installation. This process began in early 2001 initially through planning for an online web-based fiducialization interface. Quadrupoles and sextupole fiducials were measured on a coordinate measurement machine while the gradient dipole magnets, vacuum chambers, and other components were surveyed in various laboratories around the SLAC site. Total stations, laser trackers, and optical tooling methods were all used to fiducialize these devices. Once fiducialized, a specific series of magnets, vacuum chambers, and other devices were assembled and aligned onto a set of support rafts (Fig. 2). Later these fully assembled and pre-aligned rafts were transported and installed onto the newly poured ring floor.

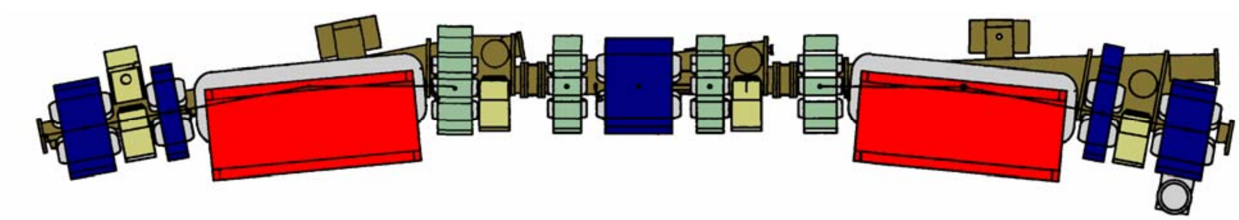

Fig. 1 Plan View of Assembled Magnets and Vacuum Chambers

Two lengths of gradient dipole magnets were designed for SPEAR3. These magnets required a special fiducialization technique that included some external “garages” that were previously aligned with the magnet using inclinometers and proximity sensors (see figure 3). These garages acted as an external extension of the magnet profile. Targets were placed on these garages as well as the magnet itself and the survey included surface scans of some key faces of the magnet for quality control checks. The survey eventually resulted in standard deviations of under 30μm for the fiducial points.

Fig. 2 Gradient Dipole Magnet (left) and Laser Tracker with Garage (foreground)

Raw data was recorded on Excel spreadsheets that performed a number of checks including garage, trolley, wire holder and surface orientation verifications. Figure 5 gives an example of a few of these sheets that were converted to pdf format and posted on an Alignment Engineering Group website for SPEAR3 personnel.

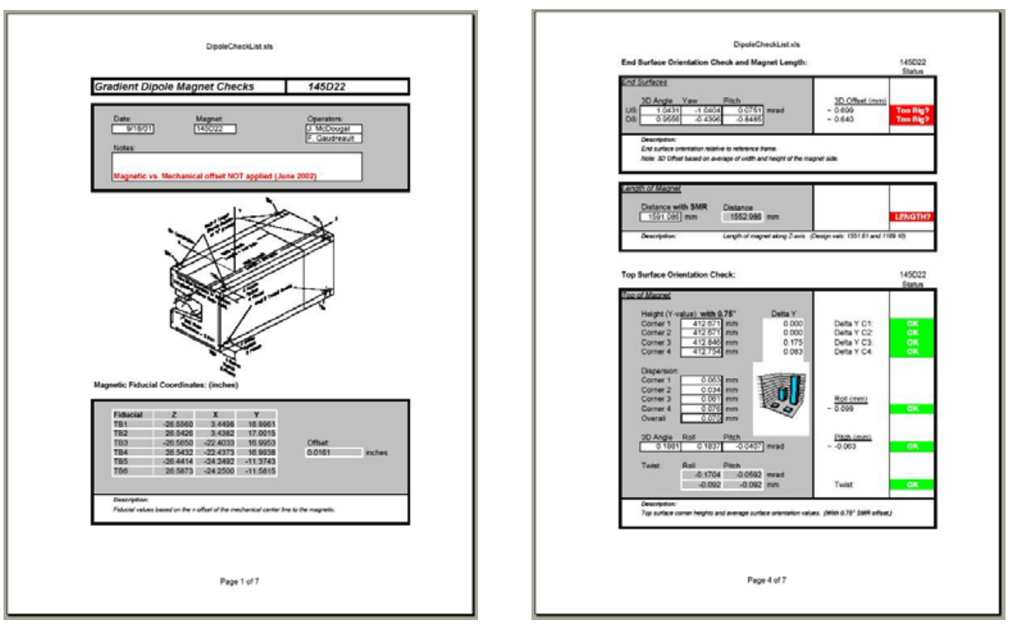

Fig. 3 Samples of Gradient Dipole Webpage Output

Two sizes of sextupole magnets and four sizes of quadrupole magnets were fiducialized using a Coordinate Measuring Machine (CMM). The magnet probe tips are checked independently and then the relationship between them was measured on the CMM (figure 5). The “yaw” plane and the z-axis of the magnet was determined by using five points to define both faces of the magnet and roll was derived from top surface measurements. A one-piece mandrel was then secured along the axis of the magnet using “G10” wedges and measured with the

CMM. This gave the physical centerline defining as the x-axis and subsequently the y-axis [1]. Various checks were performed to ensure the axes were well defined.

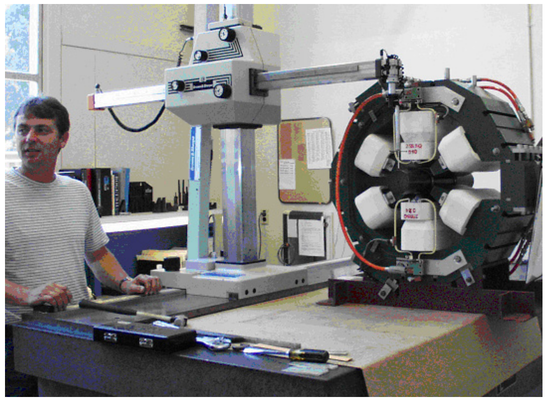

Fig. 4 Sextupole Magnet CMM Fiducialization Survey

Once the data was verified it was automatically converted into a format that could be viewed on the web. One feature of the CMM measuring process was that the data never had to be manually recorded thus essentially eliminating coping errors.

Table 1 presents the different types of vacuum chambers that were fiducialized for SPEAR3. This is the same format that was used on the website providing access to all the measurement data once again on Excel sheets.

Table 1 Types of SPEAR3 Vacuum Chambers

Vacuum Chamber Fiducialization Status	
Standard Cells	
QFC	19 of 20
BM1	15 of 15
BM2	14 of 17
Matching Cells	
MCA	4 of 4
MCB	4 of 4

Each of these newly designed chambers were measured using a dedicated laser tracker and all had to be re-measured during various stages of construction. The vacuum chambers presented a unique method necessary to establish the orientation of the local fiducial coordinate system. One of the primary desires of the designers was to orient the chamber so that the beam path inside would be as far as possible from the internal walls. For this reason a device was built that could be pulled through the chamber with three 0.5" Spherically Mounted Retroreflectors (SMRs) attached. It would give a running profile of the internal structure thus giving an optimal path. This device was called a “mouse” and is shown in figure 6. Note that two SMR nests are on the top plate and only one on the lower plate due to space limitations.

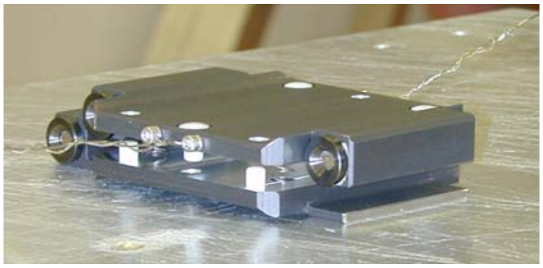

Fig. 5 Vacuum Chamber “Mouse”

Using the laser tracker which was oriented at either end of the chamber, the average path of the mouse would be measured giving the longitudinal axis of the structure (see figure 7) while flange checks and other measurements would provide roll and pitch control.

Fig. 6 Fiducialization of Vacuum Chamber

Kickers, mirrors, masks, elliptical chambers, and other special components were also surveyed prior to installation. Some had fiducials attached while others were only surface or flange oriented. Figures 8 and 9 are two examples of these components.

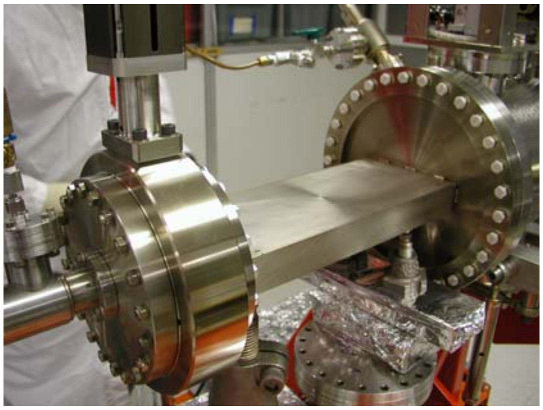

Fig. 7 Collimator

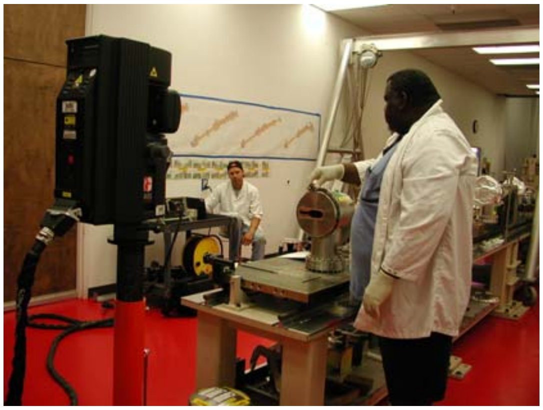

Fig. 8 Elliptical Vacuum Chamber

The fidcuials and surfaces were measured with optical tooling or laser tracker methods depending on the component in question. The fiducialization process continued during almost the entire installation phase of the ring. Components were being fiducialized as they were completed in assembly.

4. SPEAR3 Construction

The Alignment Engineering Group offered various construction related surveying support efforts. The major task of replacing the ring floor required screed rails to be carefully aligned correctly in height. This was to ensure that the specified flatness of the newly poured floor would be met. Following the concrete pour a surface profile was executed pointing out any final elevation discrepancies. This was compared to a test concrete pad that was studied in detail so that a full ASTM International Designation for flatness could be met.

Fig. 9 Surveying Screed Rails

Various surveying methods were used to determine the positioning and placement of new tunnel walls and for the assembly of large structures such as the BTS support structure. A new and difficult survey tie between the main ring and the booster was added so that the entire SPEAR3 complex would positioned under one cohesive system. In this BTS survey the lack of tunnel roof blocks that were removed for other purposes allowed better geometry between the two locations contributing to the successful placement of the BTS structure.

5. SPEAR3 Monumentation of Component Placement

Once the floor was removed and various walls changed, only four “old” tunnel monuments that were considered reliable remained. These were in the straight section areas where the floor had already been changed to concrete and surveyed years earlier. To control the new SPEAR3 datum so that the lost beam-path could be reestablished, these points along with five SSRL (building and beamline) points were added. The strategy was to select a set of points that have no special reason to have moved between phases of the project and are well observed in the new survey.

Together these points formed the new three-dimensional datum on which the rest of the new monuments would be based.

After the new floor dried and cured for a time, the new floor monuments were installed on June 13, 2003 and then a new survey tying these points with the remaining monuments was completed from June 19th to the 21st. A few days later additional monuments were placed in areas of the network that needed some densification. Eventually this network had 204 points observed with 71 laser tracker positions. The raw observations consisted of 762 distance measurements weighted at 30µm, 762 forward and reverse horizontal angles at 40µm over the distance, and 762 forward and reverse vertical angles at50µm over the distance. A separate survey for just heights gave differences weighted at 50µm. These points were distributed within the ring as well as inside the surrounding SSRL buildings. A total of 34 new floor points were added to the existing 4 from the straight regions. The outside walls had 50 points and the inside aisle wall 32 plus one ceiling point. Inside SSRL 32 points were located in the beamline areas and 25 more were from inside the SSRL building. Finally 5 points were located in the BTS area and 21 temporary points were also used.

This extensive survey thus established very well determined coordinates for all monuments allowing the next phase of marking anchor hole locations to be conducted in an accurate and timely manner. The accurate ring monuments could then be used in just a local region to resect survey instrument positions and subsequently site and mark positions for anchor bolt hole template positions.

Fig. 10 Marking Anchor Hole Locations

The templates which were checked for hole position accuracy using a small laser tracker set-up in building 26. These were used to spray paint marks of various sizes and colors for holes to be drilled and anchor bolts to be embedded in the concrete.

After the anchor bolt holes were drilled the floor was ready for installing the support plates. This was a very critical point in the assembly of SPEAR3 as the plan was to drop the girders in place with all the instrumentation already pre-aligned as well as the overall configuration having been checked and hopefully having a minimum of individual components to adjust. A point to remember is that there is no installed mechanism to move the girder as a whole since it was designed to be placed correctly the first time. Then the individuals components can be "tweaked" into position as needed afterward. To increase the chance of success for this strategy, it was decided to make another survey of the ring known as the “control survey” to confirm the position of the ring monumentation just before positioning the support plates. This survey had a totally different objective than the June survey as it was meant to primarily check that the new concrete floor had not deformed since the survey of the new monumentation. It was performed in 3 days covering 152 points through 47 laser tracker stations.

The support plates were placed in position by SPEAR3 personnel and aligned carefully by Alignment Engineering Group surveyors. Following the expertise from raft assembly area, the support plates for the girders had their alignment pins already installed and the alignment procedure was as well determined as follows:

- level the plate using the whole surface
- position in space using the pin
- set the yaw using anchor holes

The was a long and tedious procedure but crucial for the project since it enabled a great deal of subsequent surveying to be more focused just on the components located on the girder.

Fig. 11 Setting Support Plates

While the girders were placed and vacuum chambers connected between them, manufacturing, assembly and fiducialization of other components such as the straight section chambers and front end components were completed. In the ring flange positions were checked and other devices such as the SLM and RF cavities were also aligned during this time.

Fig. 12 Aligning the RF Cavities

At this point in the project time was becoming very critical. Some groups were still working on there own tasks that had entered into the allotted time for surveying. Major changes in how to finalize the alignment of the ring were presented to help facilitate a faster closure with the assurance of meeting the pre-set alignment requirements.

One item became more obvious during the installation: good positioning of the vacuum chambers was just as necessary as for the magnets. But vacuum chambers are harder to survey as they are buried inside the magnets and most of their fiducials are hard or impossible to see. The option of mapping both the magnets and the vacuum chambers would necessitate more than 75 extensive laser tracker set-ups which would have prevented other groups from working in the tunnel for several days in a row. For comparison, mapping the magnets only required 40 set-ups with nearly half of the occupation time. Another consideration was also that from various total station and laser tests conducted all around the ring, it was found that about half of the magnets had to be slightly moved primarily in y (vertically) to match the tolerance values as well as more than half of the vacuum chambers. Even though this was only for one dimension, both x and z had to be considered in this instance. With all of this taken into consideration a new strategy was presented to the SPEAR3 installation team and subsequently adopted:

- Get a final set of monumentation values using both laser tracker and leveling data
- Look locally at all magnets and all vacuum chambers and adjust them to ideal positions

In both of these cases time saving decisions were made as well as the addition of specific “original” tests:

- For the monumentation:
    - perform the level observation first
    - include 1 TB per magnet in the monumentation mapping to use it as a check for the local set-ups.

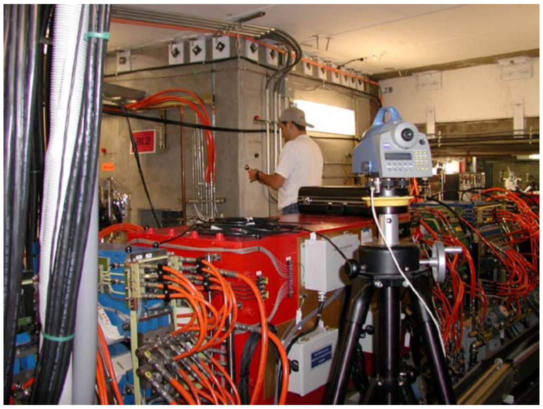

Fig. 13 Levelling

- For the magnet positioning, use TC2002 local set-ups with the following details:
  - Resection is based on a minimum of 5 points from which at least 2 are floor
  - Check with each “mapped” tooling ball

- For the vacuum chamber positioning, use laser tracker local set-ups with a newly developed “arcing technique”.

This was a valuable time saver as the height of the instrument did not have to be varied for the vacuum chamber and a 20” long extension arm allowed tooling balls deep between magnets and other components to be extended above everything allowing many less instrument set-ups.

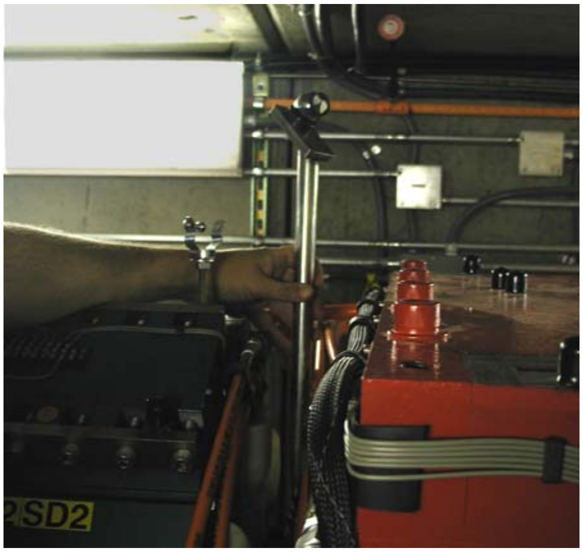

Fig. 14 Vacuum Chamber Measurement via Arcing

Thus a final survey was completed November 13th to 15th of 2003. A total of 368 points (167 monuments and 201 tooling balls) were surveyed using 40 laser tracker station positions resulting in 636 triplet observations: distances were weighted at 40µm, horizontal angles at

40μm over the distance and vertical angles of 50μm. An additional 303 height differences were added at a weighting of 60μm. The datum was defined by minimally constraining three points in the network: SM05F5 was fixed in Z and X while SM14F5 was fixed in X. The vertical direction was over-constrained using six SSRL points held fixed in height. The adjustment yielded a small datum shift of the 38 ring floor points of -38μm in Z, -187μm in X and a rotation around Y of 0.0735 mrads. With a network having a degree of freedom of 966, the a-posteriori sigma was a reasonable 1.046304 and all four observation types passed the Chi2 goodness of fit test separately and as part of the whole observation distribution. From this it was seen that most of the floor points settled between zero and 0.3 mm. The greatest settling was found in the east-straight region as shown in the following figure. This was the reason that more than half the components were thought to need adjustment in Y. In actuality, less were found to need adjustment.

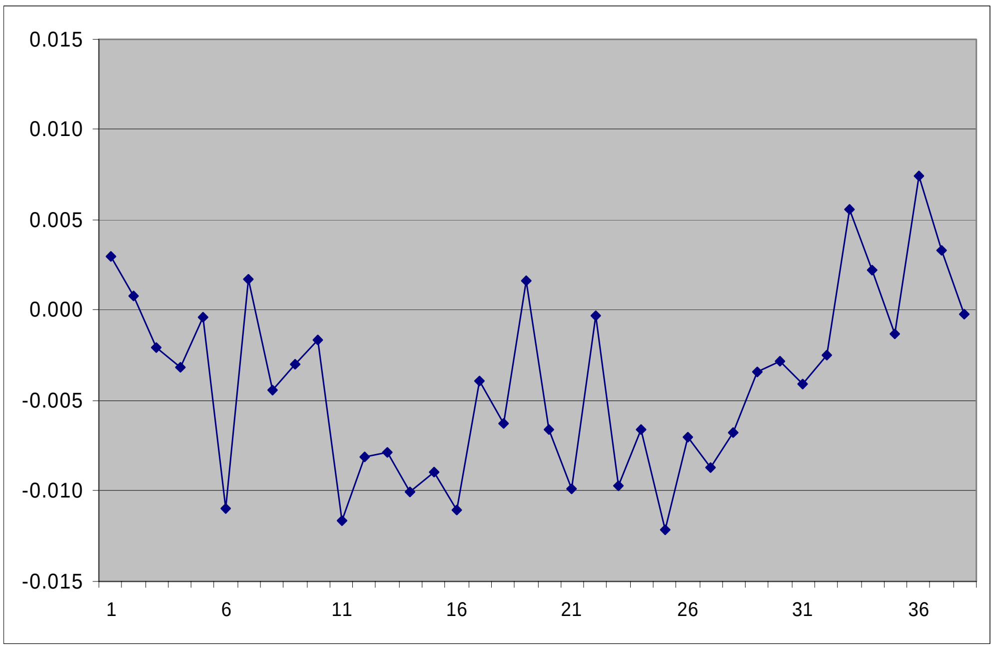

Fig. 15 Floor Monument Elevation Changes in Mils

The inner and outer walls showed a near normal distribution of movements mostly near zero as the following figure demonstrates.

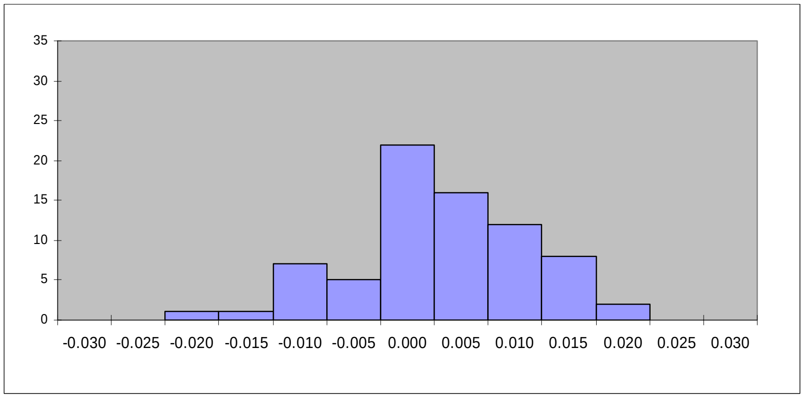

Fig. 17 Z Coordinate Change Histogram

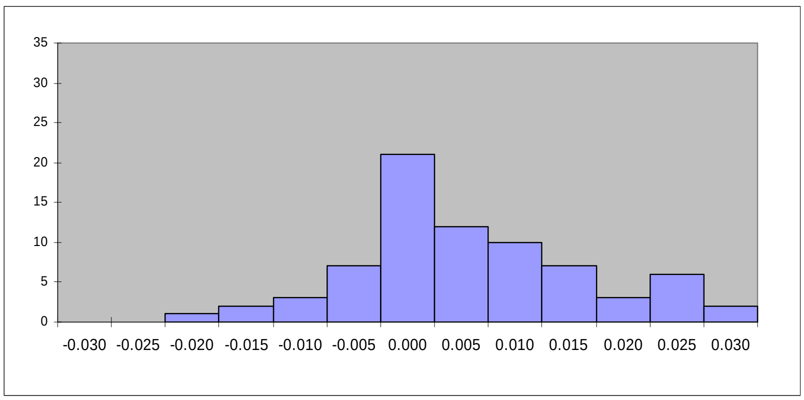

Fig. 18 X Coordinate Change Histogram

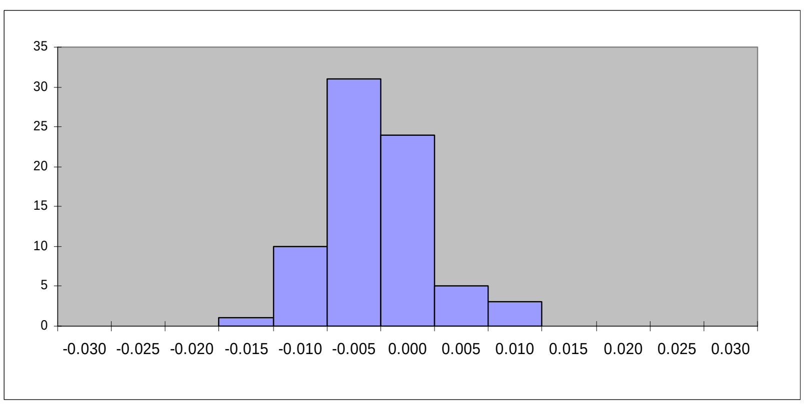

Fig. 19 Y Coordinate Change Histogram

Four surveying crews started moving the magnets on Monday November 17th using the established procedures discussed above. This extensive survey of the ring required 6 days to complete. The arcing technique using the 20” extension arm that was developed for use with the laser tracker survey of the vacuum chambers was finalized on Thursday November 20th. This required one crew 2.5 days to measure and set all the non-straight section vacuum chamber girders. On Sunday November 23rd at noon the ring was free from alignment.

6. Summary

The alignment of new SPEAR3 ring was very successful. Excellent communication, coordination and cooperation between the SPEAR3 management team and the Alignment Engineering Group lead to a new ring that was placed in its correct position and subsequently lead to a successful complete orbit of the beam at the first attempt. Extensive use of the web for communicating alignment status and results facilitated a smooth operation. In the late stages of the project, unique decisions were made and discussed that allowed the very reliable monuments placed throughout the ring to be used to finalize the positions of not only the magnets but all of the vacuum chambers.