1.0 SPEAR3 Alignment Proposal

This chapter describes procedures and methods that the alignment group will follow to position the SPEAR3 ring. All presently existing magnets and vacuum components will be replaced while most of the existing beam lines will remain at their present trajectories and new monuments will be installed where needed. Any remaining survey monuments that are in good condition will be reused. In this proposal, geodetic principles governing survey and alignment measurement space are briefly reviewed and their relationship to established SPEAR3 coordinate systems are shown. The chapter then continues with details of the activities involved in a step-by-step sequence from consolidating existing survey data through initial layout to the final alignment map.[1]

1.1. *SPEAR3 Surveying Reference Frame*

SPEAR3 will be a new ring constructed in the same position as the existing ring. The orientation of the surveying coordinate system used in the existing ring will be preserved (as discussed later in this section). In general, all measurements will be three-dimensional and made in the local 3-D reference system. A majority of the measurements will be made without reference to gravity. The center of the ring is the origin and the plane created from the beam height of the ring defines the ZX-plane. This plane will be the regional or local reference used for all observations. (Local only in terms of the earth.) Horizontal position differences between measured points on the geoid[2] or projections of points onto a best fitting local sphere or ellipsoid with those points on a local tangential plane are not significant for a small network the size of SPEAR3. Hence, it is not necessary to project original observations like angles and distances into the local planar system to arrive at planar rectangular coordinates.

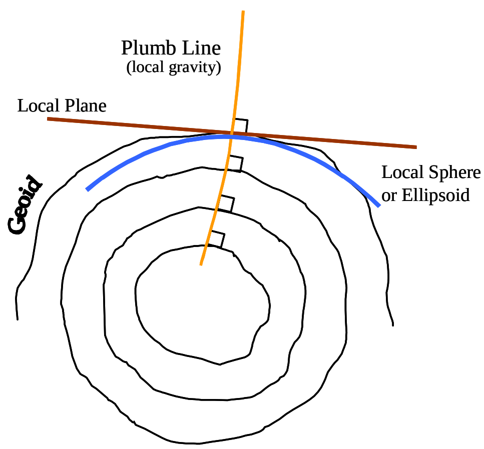

Fig. f11_a
Effect of Earth Curvature

However, for observations that are relative to gravity, the curvature of the earth needs to be considered (see fig. f11_a). If uncorrected for example, at 100 meters from the origin an 80 μm height distortion would result. Since leveling is necessary to improve the vertical positioning of the surveyed points and is carried out with respect to gravity, the reference surface is the geoid. To relate measurements that are not with respect to gravity (local 3-D) to the geoid, special software is used that rigorously takes this into account (see section 1.1.6).

1.1.1 Network Design Philosophy

A survey network is a series of instruments, targets and observations that are represented by points (3-D instrument locations or permanent or temporary target locations), and lines. Observations may be of distances, angles, heights or other quantities. With present-day computer techniques and equipment, many of the past constraints for component placement are eliminated. These were time consuming processes that involved very carefully setting up an instrument over a target on the floor. Also available lines of sight were reduced due to equipment or other components being in the way.

SPEAR3 will be observed using three-dimensional observations from “free-stationed” instruments as opposed to older methods requiring “forced-centered” instrument setups[3]. This presents a significant reduction in alignment costs due to faster set-up time and the freedom to place an instrument anywhere that is convenient. The result is having more targets available for observation and unconstrained instrument placement that will strengthen the geometry of the network. The network design will also consider other systematic error effects including lateral

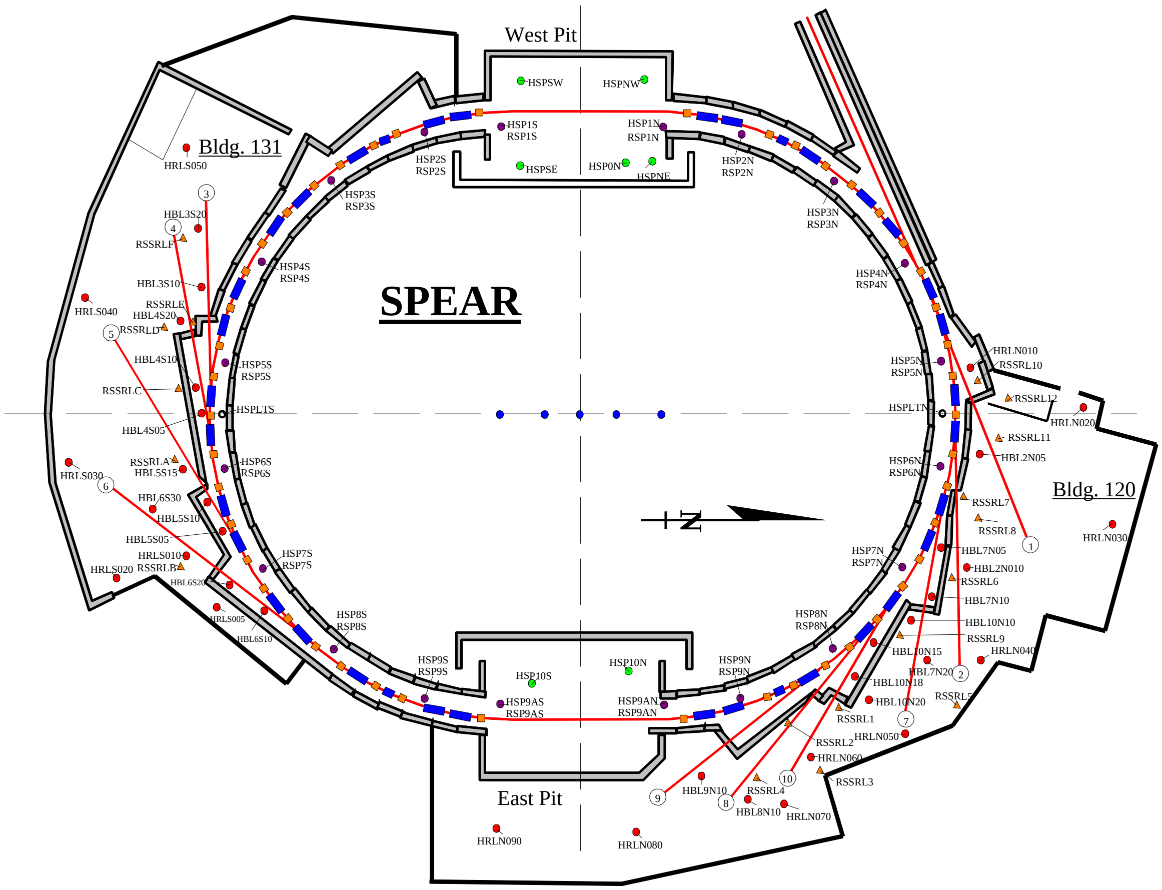

Fig. f111_a
SPEAR2 Layout

refraction[4]. Previous surveys of the existing SPEAR ring have shown some systematic errors due to refraction. Through study and updates of atmospheric models, some reanalysis of the existing survey data will be necessary. The use of existing beam lines for the future network makes this a crucial design step ensuring that the present datum will match the future SPEAR3 network.

The target reference system will also be considered in designing the network. A specially designed object placed at a fixed position acts as a point. The design of such a target becomes much easier with free stationing since we are dealing with the placement of targets only and not with the instruments. The target design is based on a 1.5" metal sphere. Different targets can be incorporated into the sphere in such a way that the position of the target is invariant to any rotation of the sphere. At SLAC, designs have been developed and used to incorporate theodolite targets into the sphere (see fig. f111_b). Tracker targets are glass and air corner cubes embedded within the sphere and are typically known as SMRs (Spherically Mounted Retroreflectors) (see fig. f111_c). Receptacles for the spheres, which are usually referred to as “nests“ or “cups“, have been designed to accommodate different functions. Designs are available for cups to be grouted into the floor and for cups to be tack-welded onto magnets. Other designs have been developed for mounting cups on wall brackets and for a “centered“ removable mounting that can be placed into tooling ball bushings.

Fig. f111_b
Sphere mounted theodolite target in reference cups/nests

Fig. f111_c
Sphere mounted air reflectors

1.1.2 Network Layout

The SPEAR3 global network consists of the synchrotron network and the beam line networks. Most of the synchrotron network will be lost through the removal of existing floors and some walls. Front end and insertion device beam line support structures will remain and so will most of the associated beam line monumentation. These monuments, along with those that remain in the east and west regions, will be used to reestablish the new synchrotron beam path so that it follows the prior trajectory.

1.1.2.1 Synchrotron Ring Network The synchrotron network’s overall geometry is dictated by the previous beam path using a number of installed target points. Permanent targets will be fixed to any new walls and the new floor for long-term orientation in an unobtrusive manner while any necessary temporary or tie points will be placed as needed. The geometry of the network will permit observing each target from at least three different stations. Instrument and target locations will also avoid weak geometry and increase position accuracy. The following sketch (fig.

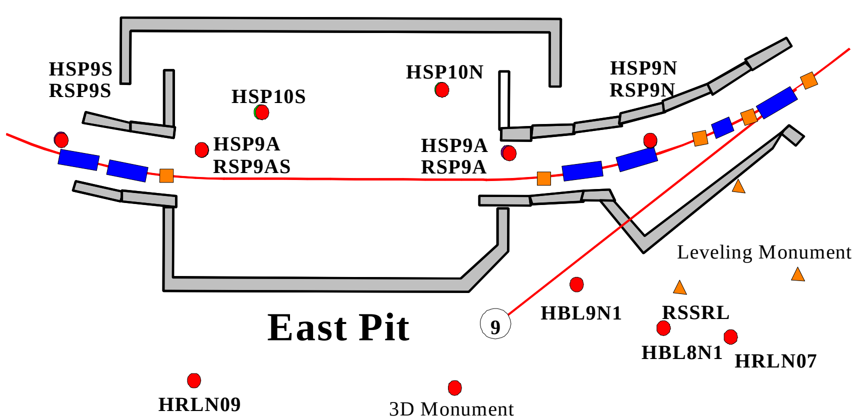

Fig. f1121_a
East Pit and Beam Line in SPEAR2 Network

f1121_a) shows a section of the SPEAR2 layout that includes a beam line and the east pit. (Note: As mentioned, some monuments in both the east and west pit regions will also remain from SPEAR2.) The survey will transfer monument coordinates into the synchrotron ring where new monuments will be placed. This is accomplished through transferring coordinates using temporary tie points both inside and outside the new SPEAR3 tunnel. This process is called “traversing” and can accurately transfer coordinates between targets even if a direct line of sight is missing. Actual positions of tie points and permanent monuments will vary according to geometrical concerns and visibility as the survey is carried out (see section 1.1.5).

1.1.2.2 Beam Line Network The beam line network serves as a reference for the installation of photon chambers and experiments. These network monuments were previously surveyed using various older techniques. They act as independent extensions of the new network and will have similar global and local accuracies as discussed in sections 1.4 and 1.5. The initial integration into the synchrotron network will be accomplished by measurements using lines of sight through open shielding wall sections around the beam lines and any other available access ports such as doors. Along a beam line, floor-targets make up the principle structure of the beam line network. Narrowly spaced beam lines have been treated as one single beam line in terms of monumentation and where the separation between beam lines becomes wider, tie points will be added if needed (fig. f1122_a).

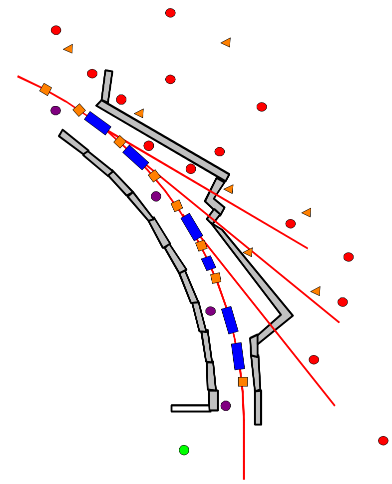

Fig. f1122_a
Section of Synchrotron Network

1.1.3 Alignment Coordinate System

SPEAR3 is 234 meters in circumference and consists of two arcs and two 7.6 meter “long straight sections”. Figure f113_a is labeled showing that the arcs consist of two 11 meter

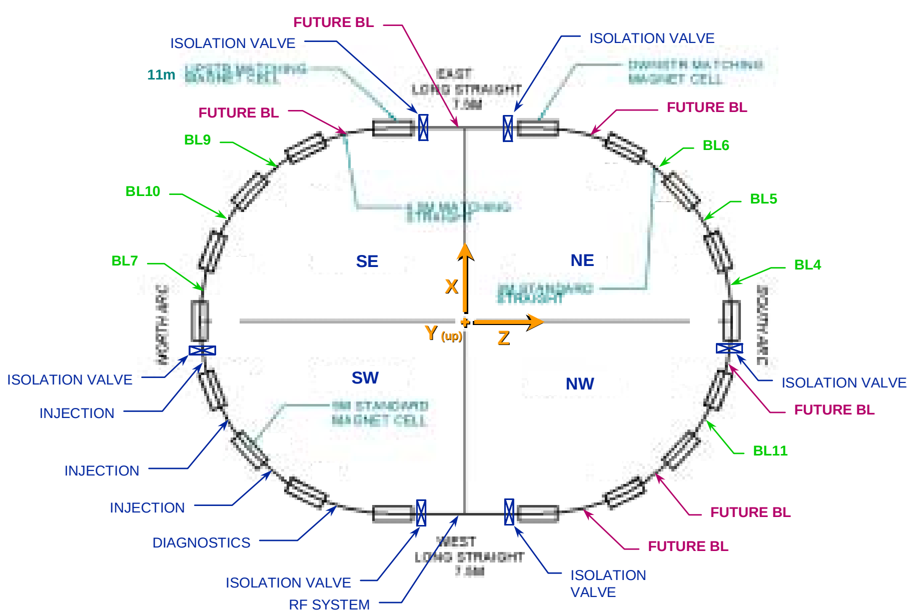

Fig. f113_a
SPEAR3 Alignment Coordinate System

matching chambers adjacent to the 4.8 meter matching straight sections, and seven 9 meter standard magnet cells joined in between by six 3.1 meter straight sections.

The alignment coordinate system for SPEAR3 is based on the existing SPEAR structure using a Cartesian right-handed system. The origin is at the center of the ring and the ZX-plane is defined by the Z-axis being parallel to the long straight sections of the ring pointing towards the south arc (between north quadrants). The X-axis is directed from the origin towards the east interaction pit (between east quadrants) and the Y-axis is on the local geoid pointing up, opposite to the gravity vector. The signs are defined by the right-handed rule (see fig. f113_a above).

1.1.5 Network Survey

The most efficient instrumentation for network observations will be a laser tracker/total station combination (figs. f115_a and f115_b). Angular and distance data along with high order leveling information (see below) will be simultaneously adjusted creating a physical and statistical map of the network.

The network measurement procedure will include two sets of direction measurements to the same set of targets in both front and reverse positions, as well as two sets of distances in both positions. As mentioned, the targets will be on the walls, floor, and on the components (i.e.,

Fig. f115_a
Laser Tracker

Fig. f115_b
TC2002 Total Station Set-up in SPEAR2

fiducial points – see section 1.3). If more observations are necessary to strengthen the network adjustment, additional laser tracker stations will be established. The procedure in other network areas will follow an equivalent strategy.

To strengthen the elevation determination, all reference targets will be observed with a standard high precision double-run level procedure. Both a Wild NA3000 and a Zeiss DiNi11 digital level, in combination with various invar rods, will be used. A detailed analysis of the network geometry, the observation plan and the required observation accuracies are being carried out. This plan includes consolidating and reanalyzing the previous survey data of the existing SPEAR ring followed by a simulation of the removal of the synchrotron network points. This will provide an assessment of the necessary geometry required to reestablish the new SPEAR3 network.

1.1.6 Data Analysis and Data-Flow

To reduce the data from the measurements, a “bundle” software package developed at SLAC is used. This software is available and has been successfully used for a number of years both locally (PEPII) and outside of SLAC (NIF). It is based on the principle where not only the position of the instrument is initially unknown (and not necessary) prior to adjustment[5], but so are the orientation values and other parameters such as scale and offsets. Adjusting data through a bundle approach means that not only positions but also orientations are computed and used to aide in the accuracy of the solution. Since laser trackers are “arbitrarily” oriented in space (most of the time though, they are roughly oriented with respect to gravity), not only their translational parameters but also their rotational orientation parameters must be treated as unknowns and become part of the solution. Any observations such as leveling that, to the contrary, are oriented with respect to gravity are included as part of the bundle solution. This provides complete flexibility in instrument positioning and allows new data to be added such as new observations.

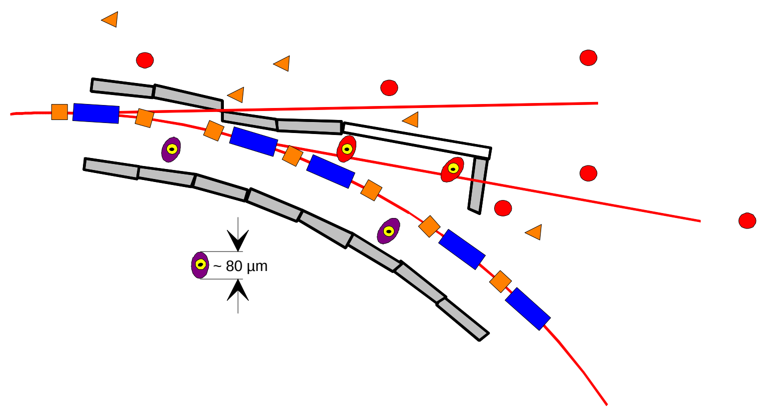

Fig. f115_c
Confidence Regions Computed After Adjustment of Observations

In SPEAR3, an important data analysis step is to gather all of the existing observational data and validate each type of observation (e.g. distance, angle, etc.) as separate contributors. (This is necessary since numerous prior surveys were made with various independent datums on SPEAR2.) Next all the observational data from prior surveys are combined and re-adjusted. The result is new coordinates for those remaining target points and, just as importantly, provisions for valuable information that can be used to determine the quality of the survey. Statistics such as error ellipses around every target or instrument or observational data are available.

To reduce errors stemming from transcription of data, the data-flow is automated. The instruments mentioned above support direct connection to field computers. This fully automated data-flow extends from field computers through data analysis to data storage. Field notes and summaries supplement this data and contain cross-references to the computer files. Measurements with any type of instrument at SLAC are guided by software derived from well-tested procedures. The software also pre-analyzes the measurements and determines and flags possible outliers before the measurement setup is broken down. This method, combined with an automated data-flow, greatly reduces errors and improves measurement consistency and reliability ultimately saving a great deal of time.

1.2 *SPEAR3 Layout Reference Frame*

1.2.1 Lattice Coordinate System

The SPEAR3 lattice is designed in a right handed beam following coordinate system, where the positive Y-axis is perpendicular to the design plane, the Z-axis is pointing in the beam direction and perpendicular to the Y-axis, and the X-axis is perpendicular to both the Y and Z-axes. This will not change from the lattice coordinate system being used for the present ring.

1.2.2 Tolerance Lists

The positioning tolerances of the magnets and other components relative to the magnetic centerline are listed below. Due to the existing beam lines, some positioning between components will be more critical than others. Each value listed in the table, from a surveying perspective, actually consists of a number of errors. The sum of these can be considered the "error budget".

Component	*Rotation rms (mrad)	*Displacement rms error (mm)		
	Roll	X	Y	Z
Bend Mag	0.50	0.15	0.15	0.50
Quadrupole	0.50	0.20	0.20	0.75
Sextupole	0.50	0.20	0.20	0.75
RF cavity	0.50	0.20	0.20	0.75
Corr. Mag.	0.50	0.20	0.20	0.75
Vac Cham	-	0.20	0.20	0.50
Kicker	0.50	0.50	0.50	0.50
Ins Dev	0.50	0.25	0.25	0.50

** values based on good fiducialization values and acceptable geometry in the tunnel*

1.2.3 Relationship between Coordinate Systems

The relationship between the alignment and the lattice coordinate systems is given by the original building design and machine layout parameters but is re-established using any remaining monuments. The updated coordinates of the old monuments are simultaneously used with the new monuments to compute the new SPEAR3 synchrotron network.

1.3 *Fiducializing SPEAR3 Magnets*

The correct fiducialization of magnets and components is an important prerequisite to successful alignment in the actual beam line. Fiducials are the actual three-dimensional targets that provide a mechanical reference to the effective centerline of the component. An error in fiducialization will create the same error during final component placement and will affect the particles' trajectory. This error could be very difficult to identify in the tunnel. Each magnet or component will have its own fiducial coordinate system. The axes have the same direction and orientation as the lattice configuration described in section 1.2.1. Fiducial marks are measured on each component to about 80 µm.

1.3.1 Fiducialization: Preliminary Positioning

Knowledge about the relative position of dipoles, quadrupoles, sextupoles, and other components is one of the key factors in the correction scheme for the synchrotron's closed orbit. This must be weighed against the absolute positioning requirements so that the present beam path will once again be established in SPEAR3. The BPM alignment is mechanically based on adjacent components and will not require direct survey measurements.

Measuring the position of fiducial marks on a component with respect to its centerline to better than 80 µm is the goal. This allows most of the error budget to remain for the actual placement of the component in the tunnel. Before actual fiducialization can proceed, opto-mechanical and opto-electrical measurements are made to place the magnet in a laboratory setup so that attitude parameters can then be determined. Depending on the component, fiducialization proceeds by measuring the mechanical center of the component and then relating it to the magnetic centerline (if applicable) and the fiducial marks using the laser tracker and other instrumentation.

1.3.2 Fiducialization of a Gradient Dipole Magnet

The gradient dipole magnet is a unique device that accomplishes both bending and focusing (fig. f132_a). To fiducialize this component, the mechanical centerline is determined as is the magnetic centerline from one survey consisting of five or so instrument stations.

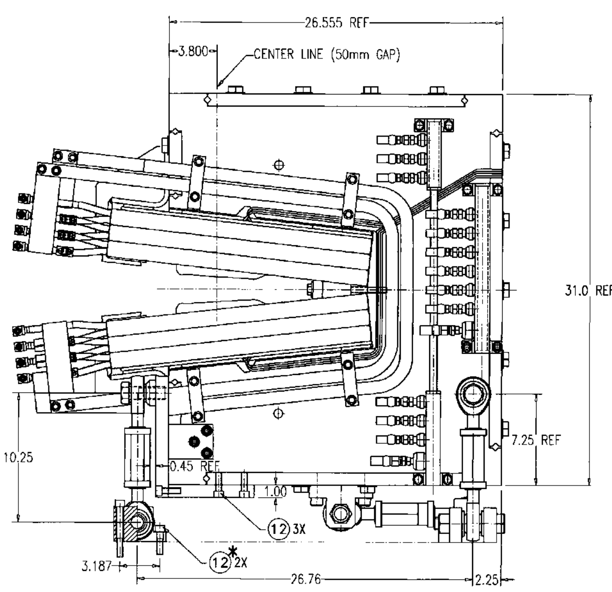

Fig. f132_a
Gradient Dipole Magnet and Supports

The dipole magnet is mechanically leveled to remove roll and pitch. Accurately machined and measured plates called "garages" are placed about 50 cm away from either end of the dipole magnet (see Fig. f132_b). They have a profile that exactly matches the core of the magnet and act like an accessible extension of the core. These garages and the core itself are all aligned by using a probe arm with capacitive sensors attached to the end. The probe arm travels in the Z-direction on a highly stable trolley riding on a rail system that is carefully leveled. The garages and probe arm are also leveled to ensure everything is lined up as well as possible. A laser tracker is then used to measure the center point of the upstream garage that defines the X and Y components of the mechanical centerline. The Z-direction is defined as the line determined by the extreme upstream and downstream positions of the trolley. To place the origin of the dipole fiducialization coordinate system inside of the magnet, a scan of datum surfaces at both ends of the magnet is made using the laser tracker. From this the midpoint is computed.

The magnetic center is found by the placement of a stretched wire within the magnet itself. The wire is translated in the X-direction until it is magnetically centered. Y is not measured at this stage. (It is solely defined by the mechanical center discussed earlier). A laser tracker will be used to measure the ends of the wire and computations will relate the wire position to the mechanical centerline.

As a check, the top surface of the dipole magnet will be measured for roll using the laser tracker. This will provide a direct check of the roll. Another check will be to measure the back surface of the magnet (i.e. the surface on the positive x-side) to check for yaw and horizontal positioning. (Note: Both of these surface scans are just checks and are not as accurate as the actual fiducialization due to limits in the construction and structure of the surfaces of the magnet.) Finally the downstream garage will be used as a check of the orientation of the mechanical centerline through direct tracker measurement.

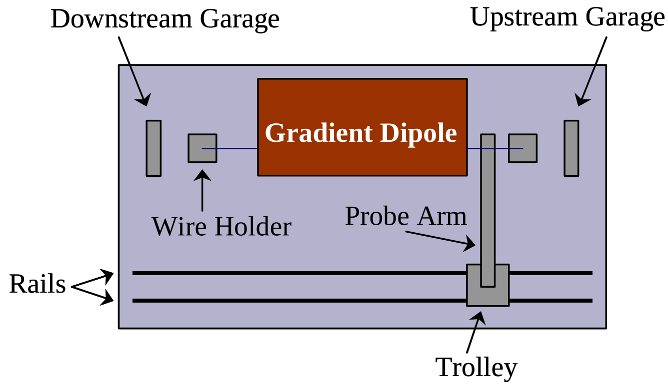

Fig. f132_b
Simplified Plan View of Fiducialization Set-up

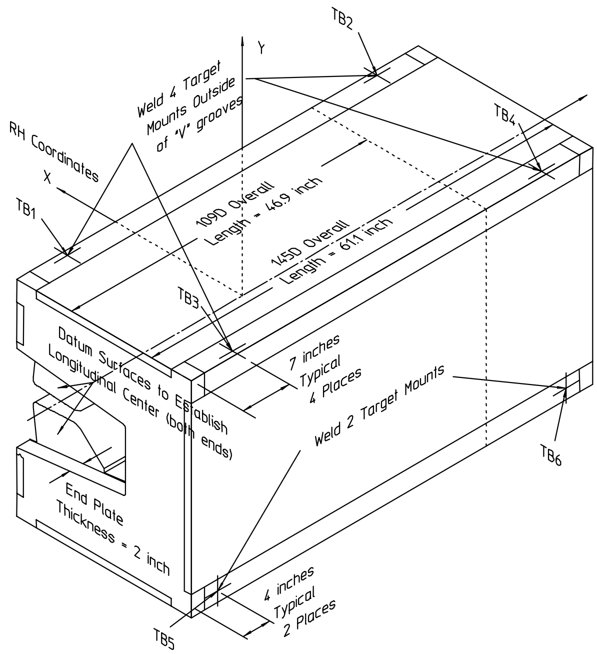

Fig. f132_c
Fiducial Positions on Gradient Dipole Magnet
(J.Tanabe)

1.3.3 Fiducialization of Quadrupoles, Sextupoles and other Components

The Quality Inspection group will determine the mechanical centerline of the quadrupoles

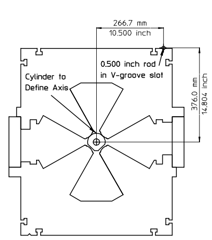

Fig. f133_a
Mechanical Centerline of Quadrupole
(J.Tanabe)

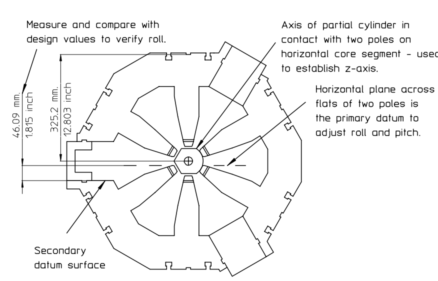

Fig. f133_b
Mechanical Centerline of Sextupole
(J.Tanabe)

and sextupoles on a Coordinate Measuring Machine (CMM). In figures f133_a and b the centerline determination of these magnets is accomplished using a mandrel. It will be placed in contact with two of the four or six poles and then the ends will be measured. In one method, the mandrel will be moved to the next two poles and the process is repeated. The result will be a circle at either end of the mandrel where the midpoint represents the defined mechanical centerline. In another method, only one position is used that is offset from this centerline. These methods were successfully used for fiducializing PEPII HER quadrupoles and the resulting centerline (or offset line) was the bases for the component fiducial coordinate system shown in figures f133_c and d.

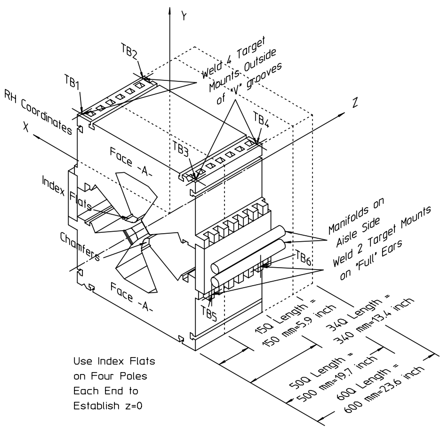

Fig. f133_c
Fiducial Positions on Quadrupole
(J.Tanabe)

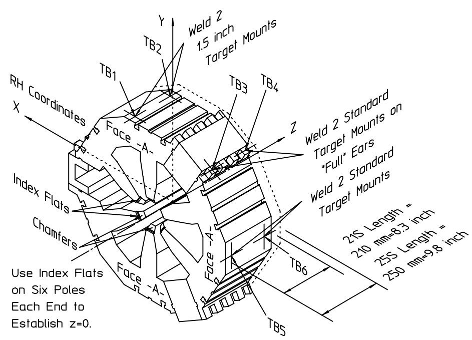

Fig. f133_d
Fiducial Positions on Sextupole
(J.Tanabe)

1.3.4 Raft Reference Marks

The origin and orientation of a raft is given by precision holes drilled into the surface of the top plate. The bottom side of the base-plate will have two pins that are used to position each raft in the tunnel onto raft support plates without necessitating any measurements (see section

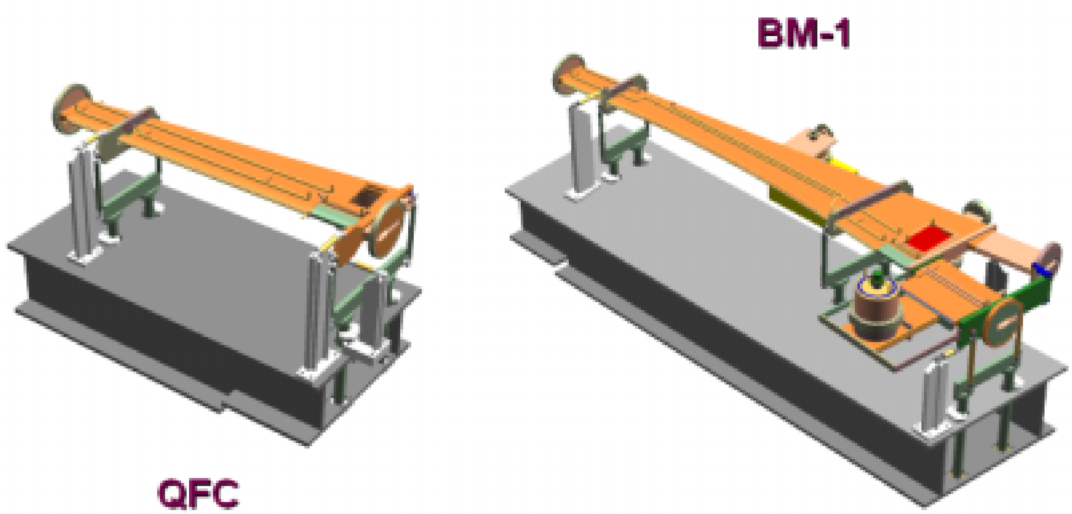

Fig. f134_a
Standard Raft Supports for QFC and BM-1 Vacuum Chambers
(BM-2 not shown)

1.4.1.2). Three rafts make up one cell consisting of BM1, BM2 and QFC components. Figure f134_a is a view of two of the three rafts that make up one standard cell with only the vacuum chambers attached.

1.4 *Field Implementation: Absolute Positioning*

In this section some of the actual field procedures are covered. Placing rafts and components to the computed positions will be very crucial since the remaining beam lines must be preserved for SPEAR3. Free-stationed trackers or total stations are used for positioning measurements. Refinement and final positioning will be based solely on laser tracker measurements that will be tied into data from the existing beam lines and pit monuments.

Prior to installation, each raft will be set up inside the collider hall with the corresponding components placed in position on top of the raft. The raft reference marks and a local network of monuments will be used for relative placement and component positioning. Once pre-aligned, the rafts, with all the components in place, will be moved into the SPEAR3 tunnel and set permanently into position using the mentioned two pins for positioning (see section 1.4.1.3 for details on the procedure and the expected accuracy). With a new survey, final precision alignment will take place.

1.4.1 Synchrotron Absolute Positioning

Each raft, carrying quadrupoles, sextupoles, corrector magnets, vacuum chambers and instrumentation will be elevated to beam height by two pedestals sitting on the concrete floor.

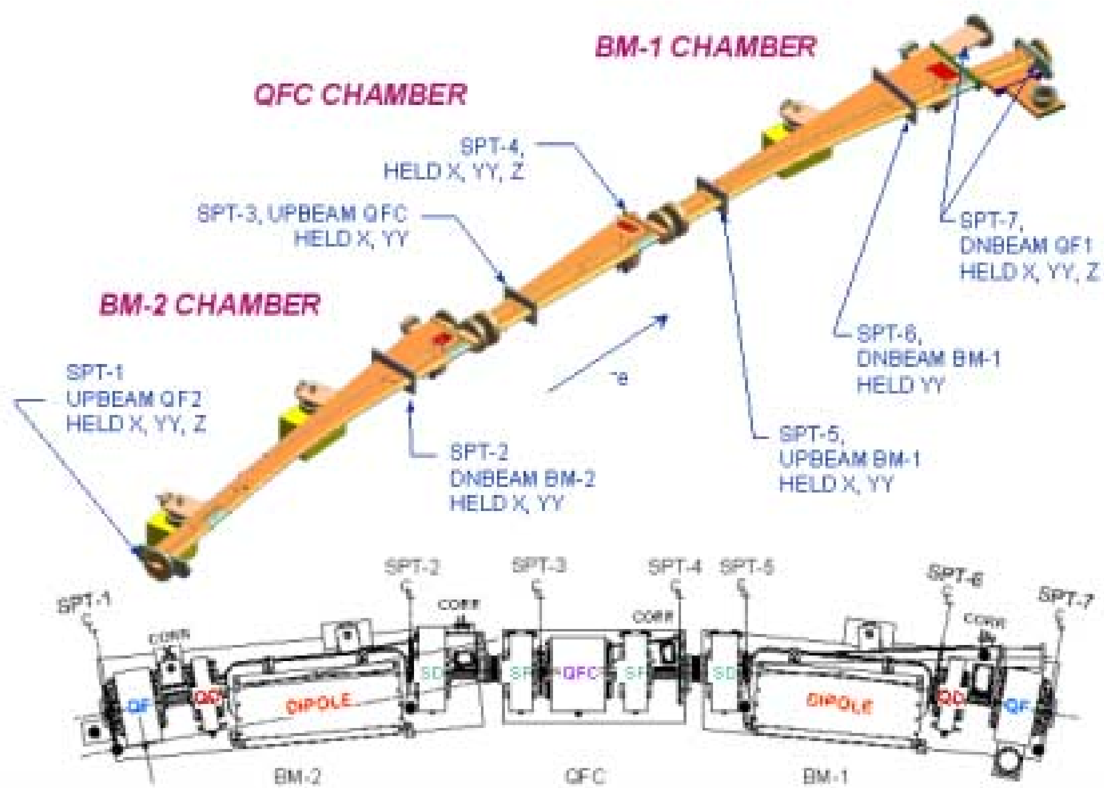

Fig. f1411_a
Standard Raft Support Layout
Including All Three Vacuum Chambers

These pedestals are positioned through a “blue-line” survey and the rafts are placed on them as described below.

1.4.1.1 Internal Alignment of SPEAR3 Rafts A set of three rafts makes up one SPEAR3 cell (see section 1.3.4). The components are pre-aligned on top of each raft using a local survey network established around the set up. This set up is in building 750 (the collider experimental hall) where there is enough room around a typical raft set for good local geometry. Once the components are positioned on the raft, the vacuum chambers are moved to position. Data from the fiducialized chambers are used to place them into position on the raft. Then, with all of the components installed around the vacuum chamber, the raft is ready for transport and installation into the SPEAR3 ring where final alignment will take place. Depending on the raft design, components may shift position. Whether or not they shift, a final global survey is necessary in order to ensure the final positioning tolerances are met. (A completed raft will be placed in the tunnel within about 0.5 mm of the design position before final alignment.)

1.4.1.2 Raft Anchor Hole Layout Survey. Positioning the rafts into the SPEAR3 tunnel requires anchor bolts to be embedded into the new concrete floor. Two sets of bolts are placed at either end of the raft section where a raft support plate will be placed. (Fig. f1412_a) The position of these bolts is established during the anchor layout survey where the position of each bolt is marked on the floor. A standard template is fabricated that indicates all anchor holes. This significantly reduces the number of individual layout pointings. A total station or laser tracker position can locate and position the template with only two pointings. (i.e., two pointings will position two of the template holes allowing the remaining holes to be easily marked.) Before the holes are marked, the location of the template will be checked from a second station. In the sequences of work, the last station can then serve for the n+1 raft as its first station. Specialized software improves the efficiency and reliability of this task.

Fig. f1412_a
Setting Orientation and Height of Raft Support Plate in PEPII

The result will be two plates that are set in position for one raft. One plate will have a hole where the pin from one end of a raft will be dropped into place. The other plate will have an elongated hole in the Z-direction where the other pin from the raft will more easily slip into position (and not over-constrain the position of the raft). The first hole will position the raft in translation while the elongated hole will only control yaw. Pitch and roll as well as vertical positioning of the raft is controlled by surveying the height of the supporting nuts placed on the anchored bolts. This process will be shortened by only surveying one of the nuts and using a simple level to set the height of the others.

1.4.1.3 Raft Installation and Component Supports A total of 18 cells consisting of three rafts each will be installed in the SPEAR3 tunnel (see section 1.1.3). As mentioned, four of these cells are known as matching cells and are the last cells before the long straight sections. The remaining 14 are known as standard cells and are placed around the north and south arcs. SPEAR3 rafts will be elevated to design height by the placement of the support pedestals described above. Once the support is placed in position, the whole structure is grouted into place. This “freezes” the support position; no further position adjustments are possible without significant mechanical work. Each component on the raft has its own strut support system including the vacuum chambers (Fig. f1413_a). These very fine threaded struts (Fig. f1413_b and c) provide a full six degrees of freedom and are designed to minimize vibration. Pre-alignment in the collider

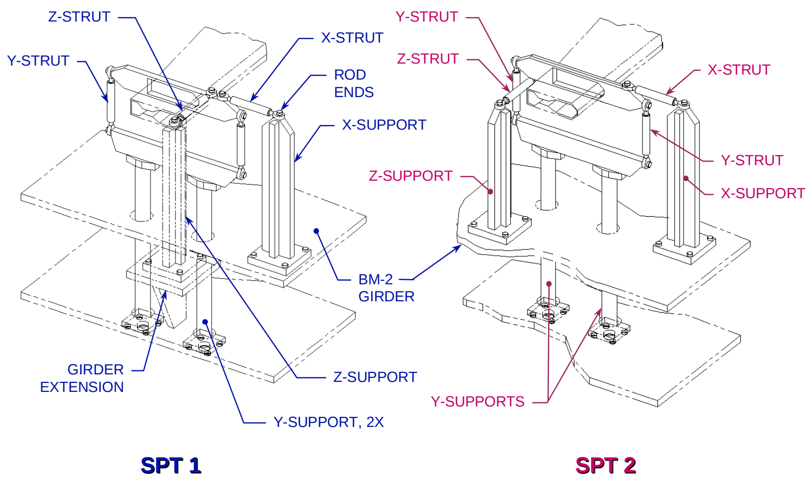

Fig. f1413_a
Standard Supports

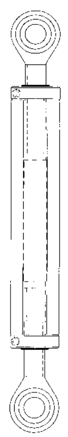

Fig. f1413_b

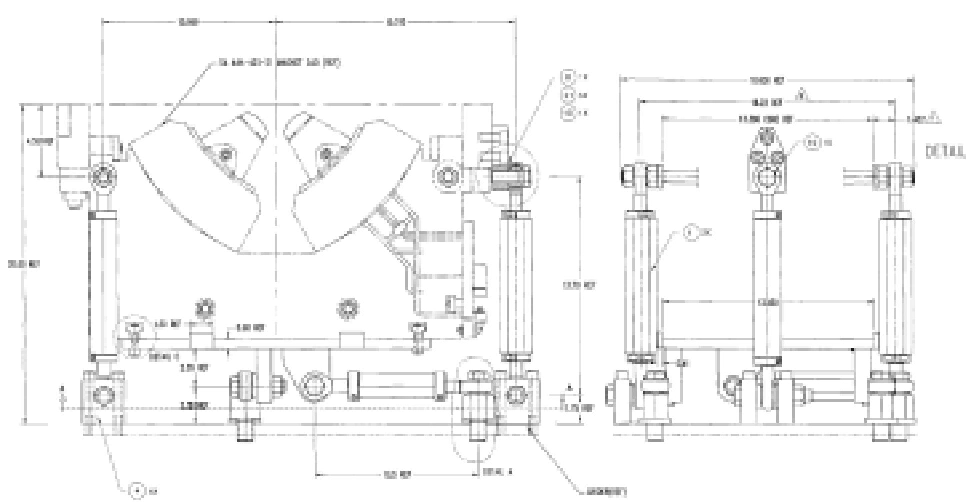

Fig. f1413_c
Quadrupole Magnet Supports

hall will have set these supports to mid-range and place the components to within about one half of a millimeter. Final alignment in the SPEAR3 tunnel will move the components into the final position within the specified tolerances. This final small movement will be independent of the raft that itself will remain fixed to the floor.

1.4.1.4 Alignment of Components

Each component will be aligned in the SPEAR3 tunnel using newly established survey monuments that were themselves placed according to the criteria described earlier. Through the survey that was used to place the monuments, each component will effectively be tied into any remaining monuments allowing the re-establishment of the old beam path. Global (absolute) accuracies of about 250 μm at 1σ are expected.

This process will be coordinated with the installation crews so that the survey of the components on each raft will follow behind them by a few days. Prior to all this, a basic set of global monuments will be placed in and around the tunnel in various non-obtrusive locations. Due to using free-stationing (see section 1.1.1 and endnotes) the placement of these targets is very flexible and can be decided upon during their actual placement. This will have to occur soon after the tunnel's concrete infrastructure has cured and settled.

1.4.1.5 Quality Control Survey Once the above step is completed in at least one arc, the component positions will be mapped. If the positional residuals exceed the tolerance, a second iteration can be initiated by using the quality control map to quantify the position corrections, which need to be applied. Should a second iteration be necessitated, a new quality control survey is required. The long straight sections and matching cells can be included in one arc or the other but may also be aligned somewhat independent to the arcs in this absolute positioning context.

1.5 *Relative Alignment for SPEAR3*

1.5.1 Synchrotron Network

Once components that make up a large section of the ring are placed in position, a relative alignment procedure will be included to increase the component-to-component placement precision. The relative alignment of components is actually a smoothing operation that can minimize any small local discontinuities without having to move an entire arc or straight section. In any situation, even for very large accelerators, smoothing has to be applied in a logical manner or else a portion of the ring or line could distort too far from the optimal design position. This process involves careful consideration of the type of smoothing needed and resultant shape of the beam path that is desired. It is especially vital to avoid any distortions in order to preserve the designed beam path. Smoothing will be used to increase the precision of component placement within any local region of the ring. For example, over the length of three rafts a relative accuracy of less than 100 μm at 1σ can be expected.

1.6 *Instrument Calibration*

Equipment must perform to its optimal accuracy so that the surveys used for SPEAR3 are of the highest quality. Calibration and basic maintenance is a regular process that the SLAC

Metrology Department conducts on site. The facilities include a laser interferometric automated tape bench and an on site alignment laboratory. Thus quality and turn-around time are optimized.

Notes and Bibliography

[1] For more information see also: Ruland, R.: Magnet Support and Alignment, in: H. Winick, Editor, Synchrotron Radiation Sources - A Primer, pp. 274 - 304

[2] The Geoid is the reference surface described by gravity; it is the equipotential surface at mean sea level that is everywhere normal to the gravity vector. Although it is a more regular figure than the earth's surface, it is still irregular due to local mass anomalies that cause departures of up to 150m from the reference ellipsoid. As a result, the geoid is nonsymmetric and its mathematical description nonparametric, rendering it unsuitable as a reference surface for calculations. It is, however, the surface on which most survey measurements are made as the majority of survey instruments are setup with respect to gravity. For SPEAR3 the laser tracker will be the primary instrument that will not be referenced to gravity. This is not a disadvantage since our bundle software "LEGO" can use gravity dependant or independent data.

The reference ellipsoid is the regular figure that closely approximates the shape of the earth, and is therefore widely used in astronomy and geodesy to model the planet. Being a regular mathematical figure, the ellipse is the usual surface on which calculations can be made. On the other hand, modern 3-D approaches, especially for small networks, will not use any reference surface for positioning. An approximate reference surface will be used to approximate gravity-based observations only. This is based on the size of the region being measured. For a network the size of SPEAR3, an appropriately sized reference sphere will closely approximate the shape of the earth.

[3] "Forced-centering" is an older technique where an instrument is set up over a known point. This process requires careful consideration of the vertical line-of-sight from the instrument down to the point on the floor. Any error in setting the instrument over this point will be transferred to any other points measured from that instrument. The newer technique of "free-stationing" allows the instrument's position to be flexible. Thus instrument position (and even orientation in some cases) is chosen solely following considerations of geometry, line of sight and convenience. To determine the instrument position, at least three points, whose coordinates are already known or are part of a network solution, need to be included in the measurements. This process is known as "resection".

[4] Lateral refraction is caused by horizontal temperature gradients. In a tunnel environment, the tunnel wall is often warmer than the air. This can create somewhat stable vertical temperature layers with gradients of only a few hundredth of a degree Celsius per meter. If one runs a traverse close to a tunnel wall on one side only, the systematic accumulation of the effect can be significant. E.g. during the construction of the channel tunnel, a control measurement using gyro theodolites revealed that after about 4 km they had already veered about 0.5 m off the design trajectory.

[5] In surveying, adjustment refers to the adjustment of statistically independent or dependent observations through least-squares estimation of the unknown parameters and the correction (adjustment) of the observations creating a self-consistent model. When the observations are dependent, adjustment of these observations is characterized by means of inverting a fully populated covariance matrix of the observations. Further details can be found in literature such as "Geodesy: The Concepts" (1986).