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# SURVEY AND ALIGNMENT OF HIGH ENERGY PHYSICS ACCELERATORS AND TRANSPORT LINES*

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Abstract

This talk summarizes the survey and alignment processes of accelerators and transport lines and discusses the propagation of errors associated with these processes. The major geodetic principles governing the survey and alignment measurement space are revisited and their relationship to a lattice coordinate system shown. The paper continues with a broad overview about the activities involved in the step by step sequence from initial absolute alignment to final smoothing. Emphasis is given to the relative alignment of components, in particular to the importance of incorporating methods to remove residual systematic effects in surveying and alignment operations.

## INTRODUCTION

Survey and Alignment's charter in building accelerators and beam lines is the physical positioning of machine components, particularly magnetic quadrupoles, sextupoles and dipoles as well as diagnostic devices, collimators and the like according to a lay-out specification, the lattice and its tolerance list. This very general task description can be broken down into six major subtasks:

1. *Survey Reference Frame* The first step is to define and physically establish a survey coordinate system appropriate to the project site and size. Control monuments are established to represent this reference grid.
2. *Lay-out Description Reference Frame* The beamline is designed and specified in a lattice coordinate system. Coordinate transformations, including rotations and transformations, need to be defined to relate this to the survey reference frame.
3. *Fiducialization* The fiducialization of a component relates its effective magnetic or electric centerline to external mechanical points that are accessible to subsequent survey measurements.
4. *Absolute Positioning* Beamline components are positioned with respect to the global reference grid.
5. *Relative Positioning* Local tolerances are achieved by the relative alignment of adjacent components.
6. *Circumference Correction* Manipulate smoothness trend curve to meet tolerance.

Besides being part of the construction executive branch, the survey and alignment engineer provides expertise in other areas. Three important areas of design work in which he should be involved are: i) the negotiations of positioning tolerances between the theoretically desirable and the practically achievable; ii) discussions of positional stability as this might be affected by such factors as thermal stability and ground motion; iii) early and active participation in the design of support systems for machine components to ensure that these allow the components to be realistically aligned to the required tolerances with a cost-effective effort on the part of the alignment teams.

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### Reference Frames

The goal is to define a computational reference frame, or in other words, a mathematical model of the space in which the surveyor takes his measurements and performs his data analysis. Transformation algorithms and parameters between the surveying space and the machine lay-out coordinate system need to be defined and the physical representation of the reference frame in form of the surface and tunnel networks need to be established. This topic has been discussed in detail in previous talks by Greening[1] and Robbins.[2] For further reading see Ruland.[3]

### Lay-Out Description Reference Frame

The lay-out description of every machine component is given in a document called the lattice or the "TRANSPORT"[4] run. The lattice defines every machine component and its ideal position.

*Ideal component position.*

For every new machine various computer programs are used to simulate the path of the particles. Model components bend, focus or defocus the particles as they traverse the electromagnetic fields they encounter. Component parameters are manipulated to keep them on the intended trajectory and to qualify the beam's characteristics. The result of such simulations is a sequential listing of the design components and their parameters. Most commonly, the coordinates for the beginning of the magnetic length of a component and for the beginning of the following drift-space are listed in all six degrees of freedom *in a beam following coordinate system*. In addition, a magnet's field strength, and if applicable, its bending angle is given.

### Tolerances

Based on experience and the results of lattice simulation runs, position tolerances are determined for each magnetic component and are attached to the lattice specifications. The individual specified parameters are usually the maximum permissible displacements in the direction of the three coordinates and the rotation around the longitudinal axis. The tolerance specifications usually distinguish between absolute and relative positioning. The absolute positioning tolerance defines a maximum global shape distortion by specifying how closely a component has to be placed on its ideal location, whereas the more important relative tolerance defines the alignment quality of adjacent components. The tolerance definition needs to state also the required level of confidence, and whether or not the random distribution is truncated. To achieve the equivalent of the mathematical truncation requires not only means to identify "outliers" but also to add independent redundant observations.

*Connection to surveying reference frame.*

The relationship between the surveying and lattice coordinate systems is defined based on project and topographical considerations. For small or even medium sized projects like light sources it is easy to define a common origin. For projects the size of the SSC it becomes more involved. Geological, geophysical, tunnel construction and also radiation shielding considerations enter into the definition process. But in any case the result is a definable transformation matrix.[5]

## FIDUCIALIZATION

Fiducialization is a fancy name for relating the effective electromagnetic axes of components to some kind of mark, that can be seen or touched by instruments. The alignment process is one in which we move a component's reference marks to its nominal coordinate. The beam, influenced only by the electromagnetic field of a component, knows nothing about fiducials. We have, therefore, to relate the magnetic axis to the fiducial marks with the same care if not greater, as we do the final positioning.

Magnets in accelerator beam lines have, for the most part, been made with ferromagnetic poles and traditionally these pole surfaces have been used as the references for external alignment fiducials.[6] This practice assumes that the magnetic field is well-defined by the poles (which fails in the presence of saturation). It also fails in the case of superconducting magnets, which have no tangible poles. There are other well-known difficulties: the poles of an iron dipole are never perfectly flat or parallel. Where then is the magnetic mid-plane?[7] The equivalent problem for qua-drupoles or sextupoles is that there is no unique inscribed circle that is tangent to more than three of these poles; this makes it quite difficult to describe where the centerline really is.

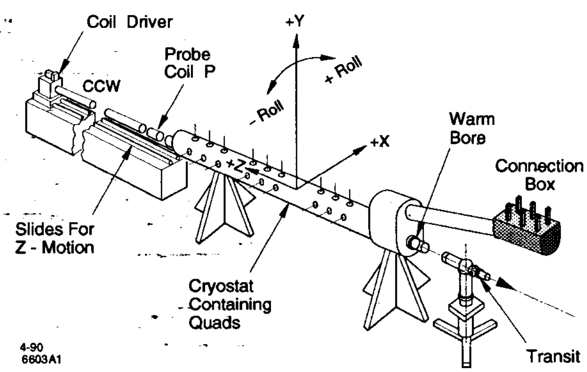


Fig.1 Fiducialization set-up of superconducting triplet quadrupoles for SLC/SLD

The only way to avoid these problems, is to use magnetic field measurements to establish fiducials. This has already worked successfully for a number of projects like the alignment of multiple permanent quadrupoles in drift tube linac tanks in Los Alamos,[8] the SLC/SLD supercon-ducting triplet quadrupoles (Fig. 1), the HERA superconducting proton ring magnets[9] and is the method of choice for the Final Focus Test Beam project at SLAC.[10]

ABSOLUTE POSITIONING

Efficient computer-aided methods and procedures have been developed to increase positioning productivity, accuracy and reliability. These techniques have been tested and proved in the alignment of SLC,[11] HERA[12] and LEP.[13] Consequently, for the absolute positioning task, a six step survey and alignment cycle is proposed:

Step 1 "Blue Line" Survey, on the tunnel floor,
Step 2 Prealignment of ComponentModules/Girders,
Step 3 Rough Absolute Positioning of Components/Girders in Tunnel,
Step 4 Fine Alignment of Girder Components,
Step 5 Final Absolute Positioning of Girders,
Step 6 Quality Control Survey.

*Blue Line Survey*

In preparation for the installation of the support systems, a "blue line" survey will be performed to lay out the anchor bolt positions. This will be done from the tunnel traverse points using intersection methods. An accuracy of 5mm relative to the traverse stations can be easily achieved.

*Prealignment of Component Modules*

A storage ring lattice is made up of cells, i.e. a sequence of dipole-quadrupole-sextupole patterns. Since the relative alignment of the adjacent quadrupole-sextupole pair has a significant impact on the machine performance, it is advantageous to combine both into a single mechanical unit. This is usually accomplished by mounting both components onto a common girder or by marrying the sextupole, which is usually much smaller than the quadrupole, directly to the quadrupole. In both cases the important relative alignment can be performed in a controlled environment rather than doing this critical task in the more hostile environment of the accelerator tunnel. However, since there is usually no provision to check their alignment status after they have been installed in the tunnel, the relationship must remain undisturbed during the transportation and installation operations. This requires that the mechanical design of the girder or frame must preclude any kind of non-elastic deflection. Traditional optical tooling techniques, industrial measurement system, or if necessary, Coordinate Measurement Machine measurements can be employed to control the relative positioning.

*Rough Absolute Positioning of Components in Tunnel*

After the blue line survey, the anchors are set and the prealigned monoliths or girders will be installed, but with the anchor bolt nuts only "hand tight". At this stage, the girders' or components' adjustment systems are set to mid range; they will not be used for the rough positioning. A method designed and optimized to accomplish this task and particularly geared to machines built on inclined planes uses laser theodolites (Fig 2). Laser theodolites, set up on traverse points will visualize the virtual ideal position of reference marks. With inclinometers as roll control instruments, a girder or component with real reference marks attached will be tapped to a position where the real marks fall into the laser beam intersection.[14] Two mm relative accuracy or better can routinely be achieved.

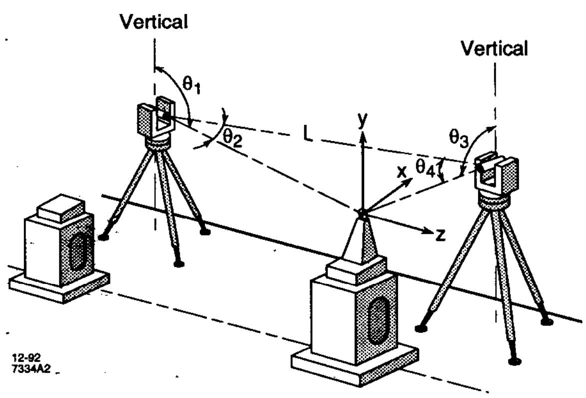


Fig. 2 Early rendering of lay-out scheme

In many cases not every component or module needs to be subjected to this routine. Given, e.g., a dipole quadrupole-sextupole module type cell sequence, only the quadrupole-sextupole modules need to be rough positioned. The intermediate dipoles can be aligned in respect to the adjacent modules. Procedures following along this line are described by Schwarz[15] and Hublin.[16]

*Fine Alignment of Girder Components*

This step is only applicable if components are mounted on a girder which does not behave like a rigid monolith but is subject to non-elastic deformations during transport from the prealignment area to its final resting place. It more or less duplicates the previous prealignment of the component module step. However, this time the components will be aligned in the girder coordinate system to achieve the final tolerances for component to component and component to girder. The first task will be to precisely level the girder; then the magnets will be brought to their ideal elevations and at the same time their pitch and roll values are set to zero using differential leveling techniques. Following the vertical alignment, the horizontal positions of the components will be set relative to the girder coordinate system. Thirdly, if required, the vacuum chamber will be positioned.

*Final Absolute Positioning of Components*

In this step, the components or girders/modules will be moved to their nominal position to within the prescribed tolerance. To avoid the accumulation of errors in positioning girders, the girder fiducials should not be used as a reference but rather fiducials of the two major components on the girder. Since the quadrupole/sextupole modules can be regarded as a monolith with an integral fiducial system, any suitable fiducial can be used. The first task will be to adjust the components to their ideal elevations and set their pitch and roll values to zero using differential leveling techniques. Then the horizontal positions of the components will be mapped relative to the traverse points using intersection methods. The mapped positions will be compared with their ideal values to determine the required mechanical adjustments.

*Quality Control Survey*

After the absolute positioning of components is completed in some logically functional section of the machine, a complete re-survey of this section should be conducted to verify the results. Quality control is better achieved by the use of independent procedures rather than the repetition of the same procedure by different teams, since data gathering with todays electronic instruments and field computers is to a large extent error-free due to on-line data validation, thereby eliminating the personal factor.[17,18]

## RELATIVE POSITIONING (SMOOTHING)

### *Philosophy*

The absolute accuracy obtained in the absolute positioning step is the quadratic sum of many random errors (surface network, transfer of control through penetration shafts, tunnel control, magnet fiducialization, magnet lay-out, *etc.*) plus the linear sum of any residual systematic errors (instrument calibration, forced centering, set-up over control points, velocity correction of light, horizontal and vertical refraction, *etc.*). The typical error envelope for the absolute alignment of a beamline is cigar-shaped; it is a minimum (but never zero) at the control points and grows to reach a maximum mid-way between two successive control points (Fig. 3). The measured reference line oscillates somewhere within this error envelope. Its absolute position cannot be pinned down any more precisely than the size of the error envelope, and deviations within this envelope are statistically insignificant. However, within this absolute error envelope, relative errors between adjacent magnets should be smaller: the major error sources affect equally the positioning of adjacent components with the result that relative alignment accuracies are significantly higher than absolute alignment accuracies. Consequently, successive surveys will reveal reference lines of different shape whose absolute position floats around randomly within the cigar-shaped error envelope. An important implication of this is that the *absolute* comparison of independent surveys "would be a nonsense"[19] when trying to evaluate differences smaller than the width of the absolute error envelope. If attempts are made to proceed with final absolute alignment, the "nonsense" is that successive rounds of survey and alignment do not converge, *i.e.*, do not result in reducing the magnitude of the misalignments. All that is happening in this case is that the components are being moved back and forth within the error envelope.

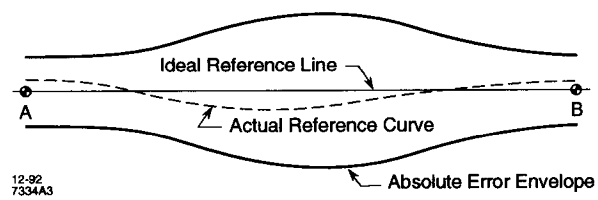


Fig. 3 Absolute positioning error envelope

Because of these problems, the absolute positioning technique is not well-suited to achieving a final position tolerance. This problem was first recognized when the size of machines increased rapidly, stretching the distance between first-order monuments from 30 m (CERN-ISR) to 1200 m (CERN-SPS), thereby magnifying and rendering visible this effect. To overcome this problem, techniques were developed to separate relative displacements from the absolute trend curve - techniques which we now refer to as "smoothing". After the smoothing is carried out, the distribution of residuals needs to be examined by Fourier decomposition type analyses to ensure that no significant amplitudes occur at the betatron frequency.

An overview about smoothing techniques as they are applied at major laboratories and their historical development can be found in Ruland.[20]

### *The SLAC-SLC Style Smoothing*

The alignment tolerances set out for the SLC show how smoothness is more important than absolute positioning for beam transport.[21] For this machine, a global positioning envelope is set to ±5 mm for every arc magnet, while the relative alignment of three adjacent magnets should be within ±0.1 mm.

Fig. 4 The pitched and rolled "sausage-link" arc beam line

The pitched and rolled sausage-link beam line formed by the arc magnets (Fig. 4) makes this modelling particularly difficult. The absolute design shape of the path is a series of curves and straight sections in pitched and rolled planes. This form does not readily lend itself to fitting with polynomials or splines. The large coupling of the horizontal and vertical also prevents the separation of smoothing operations into two components.

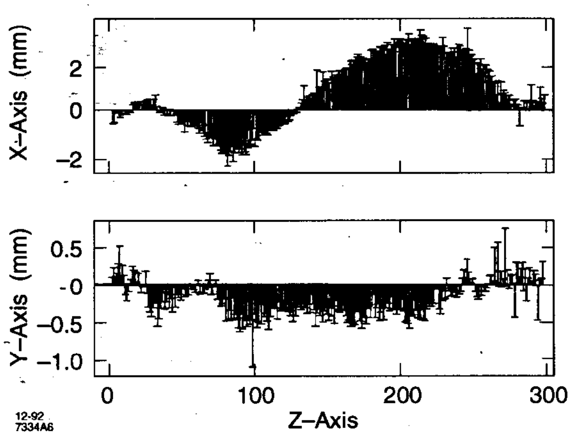


Fig. 5 Residual absolute misplacements porpendicular to beam direction

The complication of an irregularly shaped beam line was eliminated by subtracting out the actual size and shape of the beam line, leaving a series of residual misplacements for a string of magnets (Fig. 5).

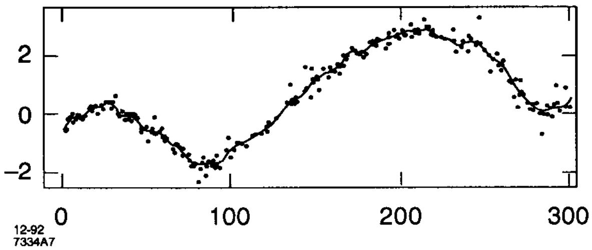


Fig. 6 Trend curve fitted through absolute misplacements

However, this step does not remove the correlation between the horizontal and the vertical components. Therefore, a spatial fitting routine was asked for; Principal Curve Analysis[22] was chosen to simultaneously pass a one-dimensional curve through the horizontal and vertical residual misalignment mapped out along the Z axis (beam direction). This curve will pass through the middle of the data set such that the sum of the squared errors in all variables are minimized (Fig. 6). The curve is *non-parametric* with its shape suggested by the data.

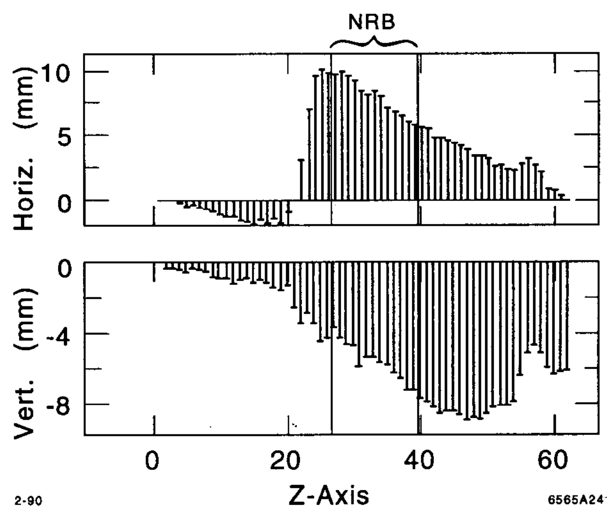


Fig. 7 Radial displacement of 12 mm caused by 1989 earthquake

The smoothing algorithm provides the options to minimize movements of the magnets on to a smooth curve and to identify outliers. If an outlier, e.g. erroneous measurement, exists, it may artificially bias the fitting routine and draw the curve away from the general neighborhood trend. For this reason a robustness estimator is included in the modelling program to weight out these points.

One improvement was suggested through experience. This involved the independent weighting of points, so that a small area of magnets can be "patched in" to existing elements. This technique proved tremendously helpful when recovering from the effects from the 1989 earthquake (Fig. 7).[23] Another improvement made it possible to deal with irregularly spaced and patterned beam line lay-outs.

### *The DESY-HERA Approach*

In the design of the HERA alignment procedure it was recognized that the fine alignment would require a smoothing process which not only treated the vertical dimension as in earlier DESY projects[24] but one which also incorporated the radial position of components. To estimate the trend curve the application of polynomials, Fourier function or cubic splines were considered. Polynomials were rejected because low order polynomials do not model the short wave length behavior of the trend curve well enough and higher order ones tend to create sine wave type resonance oscillations. Fourier functions determined by spectral analysis or Fourier transformation decomposition were found suitable but too cumbersome to use.[25] The method of choice was cubic spline functions combined with an additional target function to incorporate the smoothing goal.[26] Figure 8[27] shows the computed actual radial offsets; these offsets show rather large values where the tunnel intersects the experimental halls. Since significant temperature differences had been measured between the tunnel and these halls, it can be assumed that horizontal refraction of the angle measurements caused the large amplitudes. In Fig. 9,[28] a magnified view of the section between km 5.0 and 6.0 is shown after modelling the computed radial offset with the spline function. It can be clearly seen how well the spline modelling segregates the systematic biases. Only the differences between the computed points and the spline function will be taken care off by moving components.

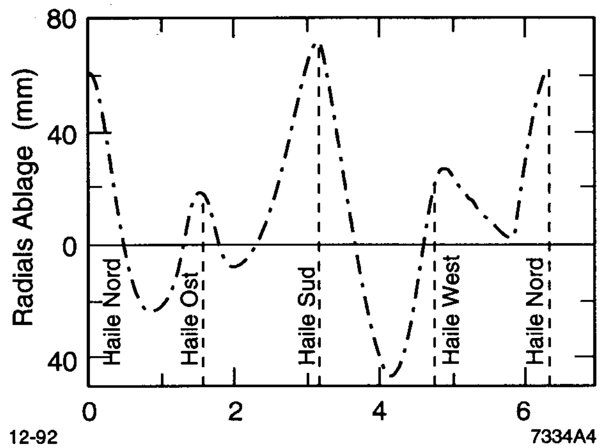

Fig. 8 Absolute radial offsets

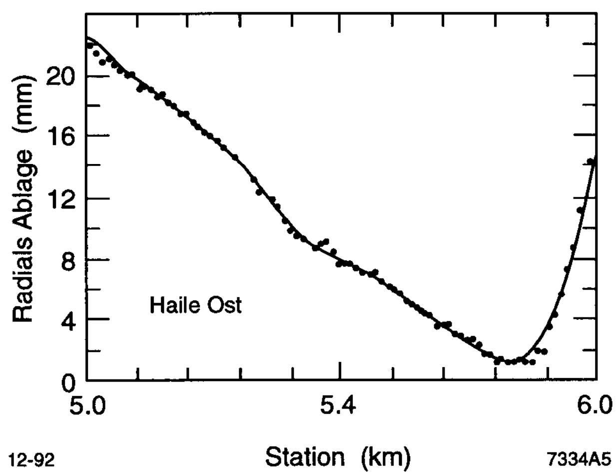

Fig. 9 Trend curve modelling of section 5-6 km

### *Smoothness Criteria*

There are two major questions to which we only have tentative answers. The question: "What is smooth?" must be answered. If the data suggests the form, then there is the hazard of too closely fitting the misalignments and not smoothing enough. Discussions with lattice physicists need to be pursued to see whether beam modelling data from computer simulation programs can help with this problem.

Smoothing is our tool to achieve *relative* alignment. But how is *relative* defined?[29] The measure by which the survey and alignment engineer judges whether an alignment operation has achieved its goal, is the standard deviation of the determined parameters. The standard deviation in fact is a product of the same least squares adjustment as the parameter itself; it is computed from the coefficients of the variance/co-variance matrix. The variance/co-variance matrix is directly related to the normal equation of the least squares operation and hence to the network configuration. If one changes e.g. the datum definition, the shape and the size of the error ellipses changes. It would therefore be desirable to define a datum-independent measure of accuracy. So far there seem to be two approaches to solve this problem. Schwarz[30] suggests using the standard deviations of the calculated perpendicular distances of magnets from a common reference line. These values could be calculated as a function of the unknowns in the same least squares routine which is run to reduce the data. At SLAC, we have for testing purposes integrated into data reduction programs a procedure suggested by Chrzanowski.[31] He developed an algorithm to compute relative error ellipses independent of the datum definition for a better prediction of break-through errors in tunnel construction.

Unfortunately, these problems have not found wide recognition and will require considerably more study.

## CIRCUMFERENCE CORRECTION

With the latest generation of machines, especially with "multi ring circus" type machines, the circumference tolerances have become very tight. Very often, the absolute positioning step cannot yield these tolerances. Therefore, correction methods have been developed at DESY and SLAC, to cope with this situation. However, it should be pointed out, if the ring has a distribution of rf cavity systems, distances between the cavities should be appropriately adjusted.

### *DESY's Circumference Correction Method*

After the smoothing step of a logical unit, one sextant or octant, is completed, a longitudinal distance survey over magnets is performed yielding, after reduction, the distances between vertex points. An integration of these distances will show the actual circumference. Comparison with the design value will give a proportional difference. The correction is created by inserting artificial smooth bumps to lengthen the circumference or by shortening the radial coordinate of a section of the ring to reduce the circumference. The spline trend estimation is applied to these sections to ensure local smoothness.[32]

### *The Approach at SLAC*

The SLAC approach is very similar to DESY's. The only difference is that the circumference reduction is incorporated into the smoothing process in such a way that the smoothing alignment correction already includes any circumference correction.

## CONCLUSION

The survey and alignment tasks described above pertain to a static situation. Under the assumption that the components are not moving significantly due to ground motion or thermal expansion of the supports or tunnel/building, then the described approach will satisfy the requirements. However, if significant position variations are to be expected, then a dynamic survey and alignment system may be called for. An example is the dynamic vertical survey and alignment system for the ESRF storage ring which is presently under construction.[33] Geophysical investigations showed that the poor soil conditions most likely would not provide the stability for a successful operation of the light source. The next generation of linear colliders will require a fully dynamic vertical and horizontal survey and alignment system. Already movements caused by daily temperature variation are expected to impede the performance of these new machines. Therefore, the FFTB project at SLAC will for the first time incorporate a dynamic horizontal and vertical survey and alignment system designed to hold the relative position of sensitive components stable to 5 mm and the absolute position to better than 30 mm.[34] It is my belief that the dynamic alignment systems will become an every-day part of survey and alignment systems as positioning and stability requirements are tightened and the technology becomes more widely available.

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