

SETTING REFERENCE TARGETS♣ *

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Abstract

Reference targets are used to represent virtual quantities like the magnetic axis of a magnet or the definition of a coordinate system. To explain the function of reference targets in the sequence of the alignment process, this paper will first briefly discuss the geometry of the trajectory design space and of the surveying space, then continue with an overview of a typical alignment process. This is followed by a discussion on magnet fiducialization. While the magnetic measurement methods to determine the magnetic centreline are only listed (they will be discussed in detail in a subsequent talk), emphasis is given to the optical/mechanical methods and to the task of transferring the centreline position to reference targets.

1. INTRODUCTION

Particles travel undisturbed on their design trajectory only when the magnetic axes of all beam steering components form a smooth continuous line in space. In addition, the axes of diagnostic instruments need to coincide with the particles' trajectory for good performance. Establishing these positioning conditions is the goal of the alignment process. The setting of reference targets is a key task in this process. These targets represent physically what otherwise cannot be accessed or referenced. In the task sequence of the alignment process, reference targets are used to represent the surveying coordinate systems (i.e. the surface net and the tunnel net), the geometric or electrical axes of diagnostic instruments, and the magnetic axes of the beam steering components.

The following definition conventions are used throughout the text: reference targets in the context of coordinate systems are referred to as *monuments*, and in the context of beam steering components or diagnostic components they are called *fiducials*. *Surveying* refers to measuring the position of an object, while *alignment* describes the action of adjusting an object's position.

2. REFERENCE TARGETS

Reference targets are used to represent virtual entities like the magnetic axis of a magnet or a coordinate system, which otherwise cannot be physically accessed. The design of the targets is a function of the survey and alignment instrumentation used with these targets, the placement location, the physical size of their host component if applicable, and the required measurement accuracy. In general, reference targets can be categorised by whether they are fixed installed targets or removable and by the number of degrees of freedom they reference.

2.1 Fixed or removable fiducials

While fixed targets have an advantage in terms of accuracy, removable targets or fixtures can have a significant cost advantage. In beam lines where hundreds of structurally identical magnets are used, a limited number of fixtures can substitute for hundreds of fixed fiducials.

2.1.1 Fixtures

Because of favourable magnetic properties, magnets are often constructed from stacked laminations. The same die is used to punch these laminations for all magnets, even for a large quantity. The dimensional features of the die can be machined to high accuracy, and are usually verified before and during use. Consequently, the mechanical dimensions of the laminations are very precise and their mechanical axis should coincide closely with the magnetic axis. Hence, it is possible to forego the fiducialization of individual magnets and instead reference the magnetic axis using clamp-on fixtures. These fixtures are seated in reference grooves and carry the actual targeting (see Fig. 1, 2).

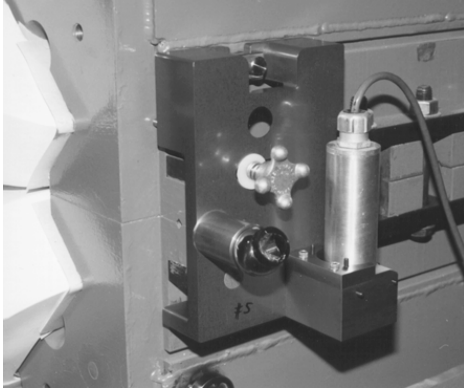


Fig. 1 Alignment fixture on quadrupole with reflector and inclinometer

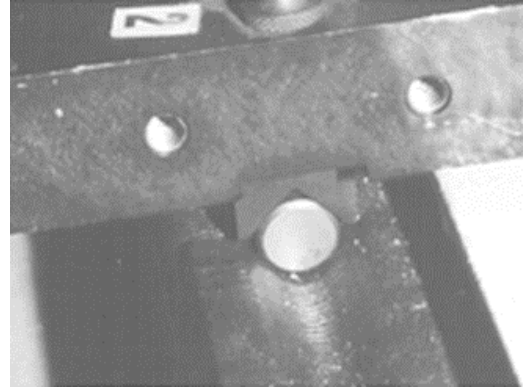


Fig. 2 Fixture referencing in lamination groove

2.1.2 Fixed fiducials

Usually, the fiducials are installed directly on the top or side of a magnet. While three fiducials, or two fiducials plus a roll reference surface are sufficient to reference all degrees of freedom, additional fiducials provide redundancy for error checking. If it is necessary to separate the fiducial from temperature caused expansion or contraction of the magnet body due to tight positioning requirements, the fiducials can be mounted on fiducial plates (see Fig. 3). These plates, made of invar, reference to the split planes of the magnet. Since the split planes do not move due to temperature, and since invar has a negligible expansion coefficient, the fiducial position can be considered invariant with temperature.

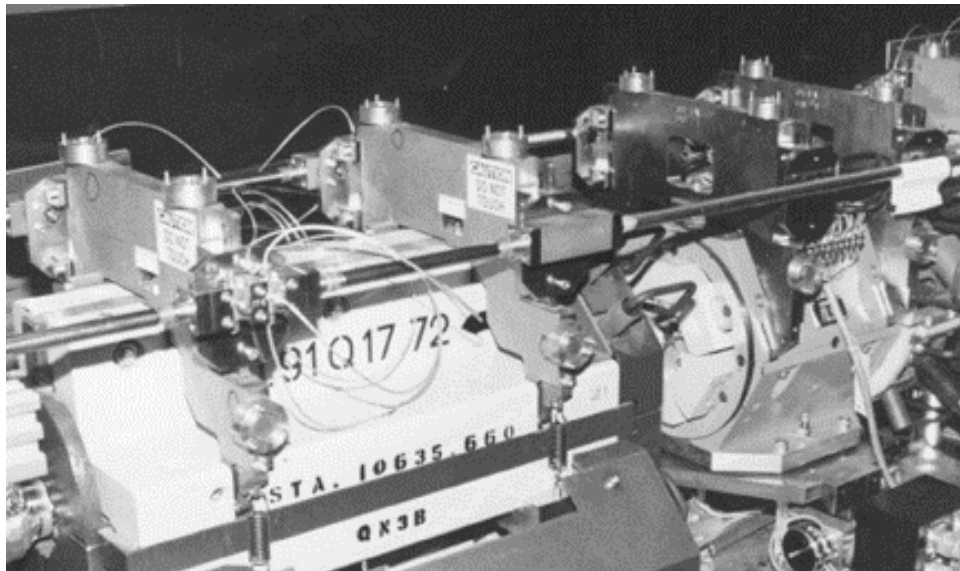


Fig. 3 Fiducial plates on magnets in Final Focus Test Beam

2.2 Fiducial and monument designs

2.2.1 One-dimensional reference targets

Traditionally, coordinate systems were represented by 2+1 D monumentation. Separate reference marks were used to represent the horizontal (2-D) and vertical (1-D) coordinate systems. Typical 1-D designs are rivets grouted into the floor (see Fig. 4) or levelling bolts set into walls (see Fig. 5).

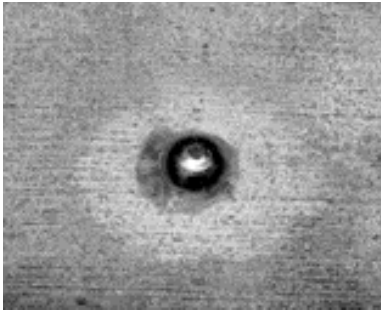


Fig. 4 Levelling rivet

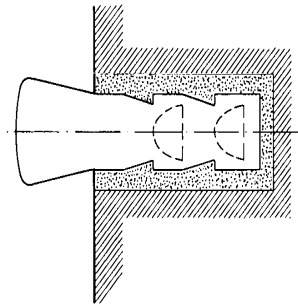


Fig. 5 Levelling wall bolt

2.2.2 Two-dimensional reference targets

The most basic 2-D reference mark can be scribe-lines on the floor (see Fig. 6, 7) or stick-on targets. A variation is the SLAC SLC floor-marks; to protect the stick-on targets from traffic wear, they are mounted inside small metal cans which are grouted into the floor (see Fig. 8). Other 2-D references are the standard Leica and Kern forced centering mounts. The Kern mount is commonly used on pillar monuments representing surface network points (see Fig. 9).



Fig. 6 Scribe line



Fig. 8 SLAC 2-D target

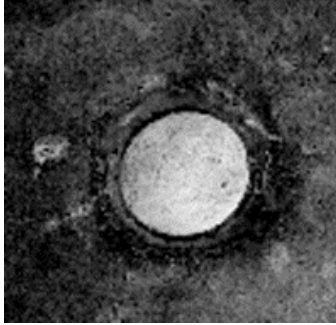


Fig. 7 Brass plug with scribe line

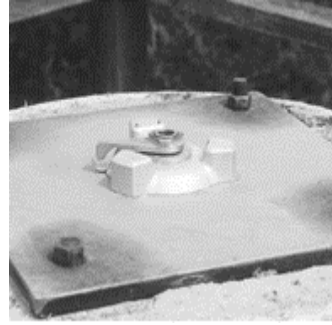


Fig. 9 Monument centering

2.2.3 Three-dimensional reference targets

3-D reference marks provide both horizontal and vertical reference.

Tooling Ball Reference The most inexpensive kind of 3-D references are tooling ball holes drilled into the bodies of components or tooling ball bushings tack-welded onto components (see Fig. 10). Common tooling balls inserted into the hole or bushing (see Fig. 11) provide an excellent reference for levelling mini-rods or optical tooling blades. For optical pointing, the tooling balls can be exchanged for targets with identical dimensions but with a cross hair or other target pattern at the exact centre of the virtual sphere (see Fig. 12). For distance measurements, reflector tooling balls are available, which have glass or air cubes mounted into the sphere such that the optical centre of the reflector coincides with the centre of the sphere (see Fig. 13). Commonly, tooling balls with either a 0.5-inch head diameter or a 0.875-inch head diameter are used.

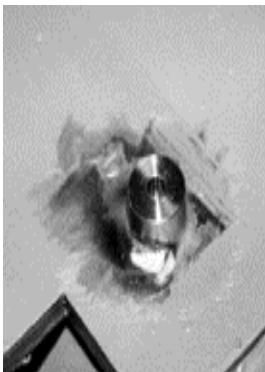


Fig. 10 Tooling ball bushing



Fig. 11 Tooling ball in bushing



Fig. 12 Theodolite target



Fig. 13 TB mounted reflector

1.5-inch Sphere System The equivalent of the tooling ball bushing for the 1.5-inch sphere system is usually referred to as a nest. A three-point mount provides a kinematic centering for the sphere. Also used are mounts with conical surfaces (see Fig. 14). As with tooling ball targets, the 1.5-inch sphere can be host to a variety of target patterns and applications (see Fig. 15). A sphere-mounted reflector with front mirror surfaces (air cube) is the commonly used laser tracker reflector.



Fig. 14 Floor sphere mount



Fig. 15 1.5-inch sphere mounted targets

3.5-inch Sphere Target The 3.5-inch standard is the evolutionary ancestor to both of the other two target systems. These spheres are a traditional item in optical tooling based alignment. As with tooling ball targets and 1.5-inch sphere targets, the 3.5-inch sphere can be host to a variety of targets (see Fig. 16, 17). However, because of its bulkiness, the 3.5-inch standard is rarely used anymore. A flavour of this size standard is the CERN socket (see Fig. 18), where a sleeve clamps a 3.5-inch sphere with a 30 mm bore onto a conical surface. This design provides the flexibility to adjust the sphere such that the bore is parallel to gravity. Using a special mounting adapter, targets and instruments can be mounted with reference to gravity on sloped surfaces (see Fig. 19).



Fig. 16 Taylor-Hobson sphere

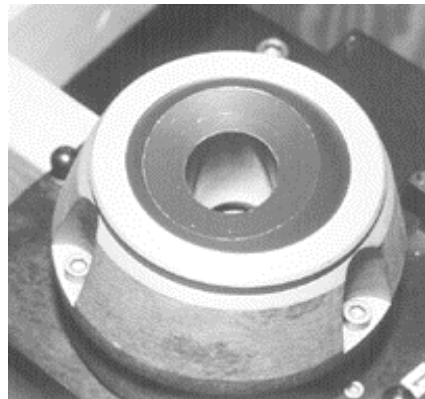


Fig. 18 CERN socket



Fig. 17 3.5" sphere reflector



Fig. 19 CERN socket with E2 mounted in sloped tunnel

3. TRAJECTORY DESIGN SPACE

Three translations and three rotations define the position of any object in space with respect to a Cartesian coordinate system. These values are a function of the design beam trajectory, the position of magnetic fields along the trajectory, and of the placement of the trajectory on our earth.

3.1 Design trajectory

Codes like MAD [1], NOMAD, or TRANSPORT [2] are used to trace the path of particles through idealised magnets. The particles' path is described by a sequence of beam elements placed sequentially along a reference orbit. The reference orbit consists of a series of straight-line segments and circular arcs. A beam following coordinate system describes the

orientation of the beam at any point along its path through the accelerator (see Fig. 20). This system remains tangent to the orbit with its positive z-axis pointing downstream. The system is rotated such that the positive x-axis generally points out from the bending arc and lies in the plane of the curve. The positive y-axis is oriented to complete the right-handed coordinate system for the local beam. To transform the local coordinates into the global system, three shifts and three rotations are applied. Care has to be taken with the sequence of the rotations and their signs (see Table 1).

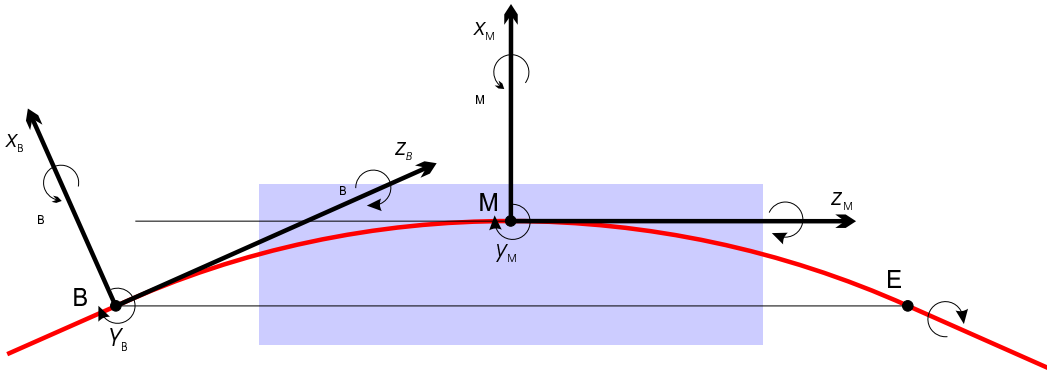


Fig. 20 Beam following coordinate system

Table 1

Rotation sign definitions [3]

	MAD	TRANSPORT	Alignment
Yaw, around y-axis θ	Positive, when z-axis turns towards x-axis	Same as MAD	Same as MAD
Pitch, around x-axis Φ	Positive, when z-axis turns towards y-axis	Same as MAD	Opposite
Roll, around z-axis Ψ	Positive, when x-axis turns towards y-axis	Same as MAD	Same as MAD

The output of the above mentioned codes gives three coordinates and three rotations for the beginning and end of each straight section and arc in the beam following system. It is now the magnet engineer's job to design a component, which replicates its virtual cousin's parameters.

3.2 Magnet reference target parameters

3.2.1 Magnet coordinate system

The parameters of the reference targets of a magnet are defined in the magnet's local coordinate system. The u, v, w coordinate axes form a right-handed Cartesian system. The positive orientation of the axes is defined in the same way as for the x, y, z beam-following local coordinate system. The datum of the u, v, w system relative to a magnet is not universally defined. While the w coordinate axis is usually coincident to the magnetic axis and the u-w plane parallel to the zero roll plane, there are differences in the definition of the origin. Often, the origin is placed where the beam enters the magnetic field. This is a virtual point and requires entering empirical data into the fiducialization process. At SLAC the

midpoint of the magnet is the origin (see Fig. 21). Since the midpoint of the magnetic length usually coincides with the midpoint of the steel length, the origin can be physically determined without knowing the difference between magnetic and steel length.

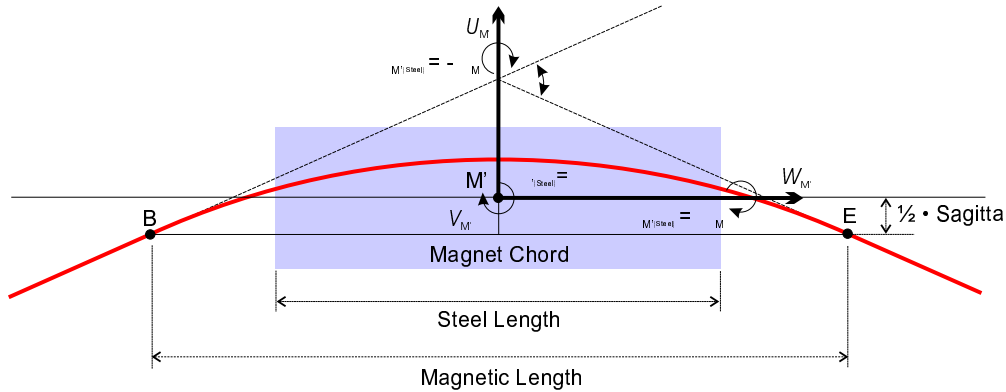


Fig. 21 TRANSPORT magnet coordinate system

3.2.2 Roll

The split planes of magnets are often accepted as the zero roll planes. However, if necessary, zero roll planes can be determined to better accuracy with magnetic measurement methods. A dipole's roll can be measured by running a horizontal wire in a vertical plane. No voltage is induced if the magnetic field is oriented perpendicular to this plane. Hence, by adjusting the magnet's tilt around the w-axis until no voltage is induced, the zero roll position can be determined. In the case of a quadrupole, no voltage is induced if a wire moves radially relative to one of the poles. If, e.g., a quadrupole's pole design position is at a 45° angle, this method allows determination of the true 45°-field plane. From there it is straightforward to determine the zero-roll position.

In some instances, a geometrical correction to the design program's roll value for dipoles needs to be applied. The w-axis of dipoles does not coincide with the x-axis of the beam-following coordinate system. Hence, if the origin of a dipole's coordinate system has been fixed where the beam enters the magnetic field, the roll value from the trajectory design program does not reflect the correct dipole roll angle (see Fig. 22). A correction, which is a function of half of the dipole's bending angle, needs to be applied. However, if the magnet's coordinate system originates at the midpoint, then the design program's beam-following roll at the midpoint is the correct physical magnet roll.

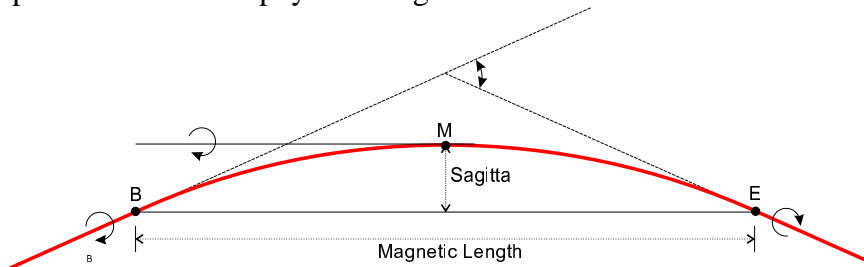


Fig. 22 Transport geometry of dipole magnet

Larger machines need to take into account the convergence of the gravity vectors (see Fig. 23). While in circular machines magnets at diametrically opposing locations are at the same elevation, their ideal roll values need to be corrected. E.g. for PEP-II the correction amounts to about 0.15 mrad, SSC magnets would have needed a 1.5 mrad correction. Also,

other geodetic corrections related to the beam line's geometry may apply (see following Section).

3.2.3 Sagitta

In the dipole case the magnet is usually not centered at the midpoint, but shifted by a fraction of the sagitta height (see Fig. 21 above). This shift minimises the necessary aperture to accommodate a straight beam pipe, and moves the beam into the homogenous field region of the magnet. The amount of the shift varies. It is typically set to half of the sagitta, but two thirds are also not uncommon.

3.3 Global reference points

Global reference points are used to determine the overall shape of an accelerator. With the exception of small machines, these points represent the global coordinate system in the form of pillar monuments on the surface and floor marks in the tunnel.

3.3.1 Shape of the Earth and survey reference frames

The goal is to define a computational reference frame, i.e. 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 layout coordinate system must be defined.

Ancient civilisations realised that the earth is round, and geodesy was born when the Greek Eratosthenes (born 276 BC) first attempted to determine its size [4]. The earth is actually of a more complex shape, the modelling of which is not easy. Three surfaces are of importance to the geodesist studying the shape of the earth:

Terrain Surface The terrain surface is irregular, departing by up to 8000 m above and 10000 m below the mean sea level.

Geoid 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 150 m 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 set up with respect to gravity.

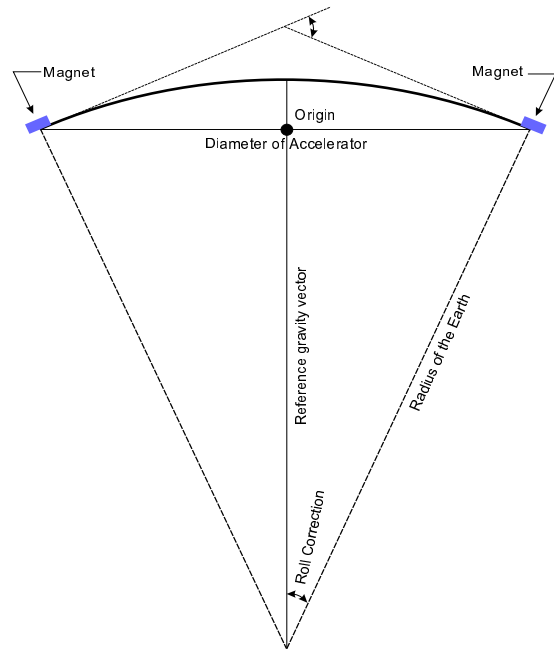


Fig. 23 Roll correction

Ellipsoid The spheroid or ellipsoid is the regular figure that most closely approximates the shape of the earth, and is therefore widely used in astronomy and geodesy to model the earth (Fig. 24). Being a regular mathematical figure, it is the surface on which calculations can be made.

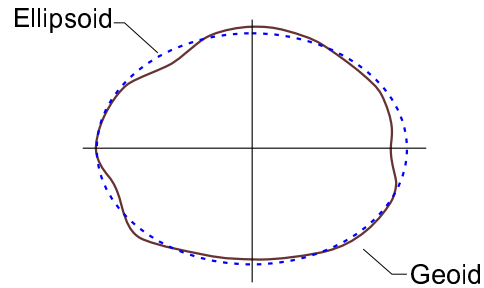


Fig. 24 Ellipsoid and geoid

In performing geodetic calculations, account must be taken of the discrepancy between the ellipsoid and the geoid. The deflection (or deviation) of the vertical is the angle of divergence between the gravity vector (normal to the geoid) and the ellipsoid normal (Fig. 25). Several different ellipsoids have been defined and chosen that minimise geoidal discrepancies on a global scale, but for a survey-engineering project, it is sufficient to define a best-fit local spheroid that minimises discrepancies only in the local area. Whatever ellipsoid is chosen, all survey measurements must be reduced to the ellipsoid before computations can proceed. This reduction of observations to the computational surface is an integral part of position determination [5]; the equations can be found in most of the geodetic literature, e.g., in Leick [6].

For large projects, the magnitude of these corrections is significant. A geoidal height determination was part of the LEP surface net measurement plan. It was found that the vertical deflections approached close to 15 arc seconds, which resulted in a separation between the local reference ellipsoid and the geoid of up to 200 mm (see Fig. 26). To nevertheless obtain a true plane in space, corrections varying between -40 mm and $+100$ mm had to be applied to the levelled elevations [7].

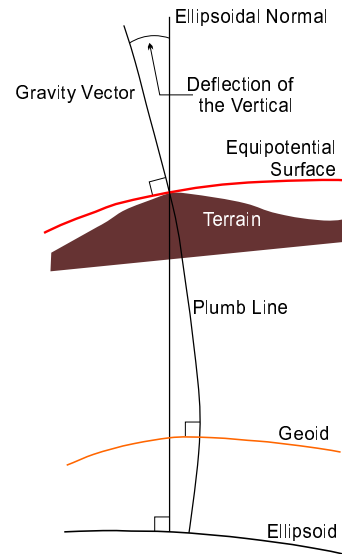


Fig. 25 Deflection of the vertical

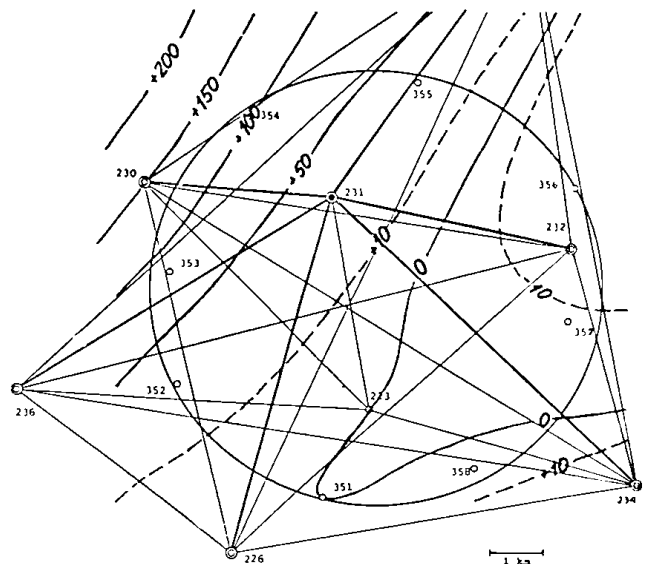


Fig. 26 LEP Geoid undulations (from [7])

3.3.2 Surveying Coordinate System

Computations with spheroidal (geographical) coordinates latitude ϕ , longitude λ , and height h are complex. They are also not very intuitive: when using spheroidal heights, it can appear that water is flowing uphill. Especially in survey engineering projects, coordinate differences should directly and easily translate into distances independent of their latitude on the reference spheroid. Therefore, it is desirable to project the spheroidal coordinates into a local Cartesian coordinate system or, going one step further, to project the original observations into the local planar system to arrive directly at planar rectangular coordinates.

A transformation is required to project points from a spheroidal surface to points on a plane surface. Depending on the projection, certain properties of relationship (distance, angle, etc.) between the original points are maintained, while others are distorted. It is simply not possible to project a spherical surface onto a plane without creating distortions [8] (see Fig. 27), but since these distortions can be mathematically

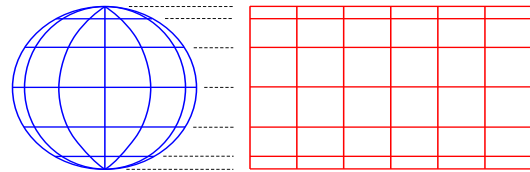


Fig. 27 Mapping distortion

modelled, it is possible to correct derived relationships, such as distances, angles, or elevations. This situation can be vividly shown in the example of the projection of levelled elevations onto a planar coordinate system (see Fig. 28). Table 2 shows the projection errors as a function of the distance from the coordinate system's origin. Notice that the deviation between plane and sphere is already 0.03 mm at 20 m.

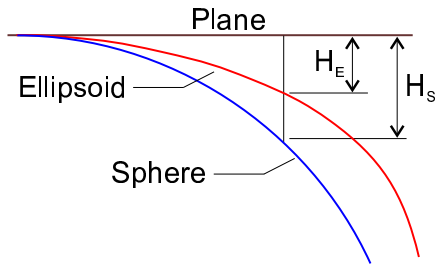


Fig. 28 Curvature correction

Table 2
Effect of Earth Curvature

Distance [m]	Sphere H_s [m]	Spheroid H_e [m]
20	0.00003	0.00003
50	0.00020	0.00016
100	0.00078	0.00063
1000	0.07846	0.06257
10000	7.84620	6.25749
25000	49.03878	39.10929

3.3.3 Survey networks

Monuments physically represent the surveying coordinate system. The coordinates of these monuments are determined using conventional trilateration or triangulation methods or, for larger size projects, satellite methods like the Global Positioning System [9].

Surface network In order to achieve the absolute tolerance and the circumference requirements, a surface network (see Fig. 29) with pillar-type monuments (see Fig. 30) must usually be established. Traditional triangulation and trilateration methods or GPS surveys can be applied to measure the coordinates of the monuments and of tripods over the transfer shafts or sightholes. Differential levelling of redundant loops is the standard method to determine the vertical coordinates. Proper reduction of measured distances also requires accurate elevation difference data.

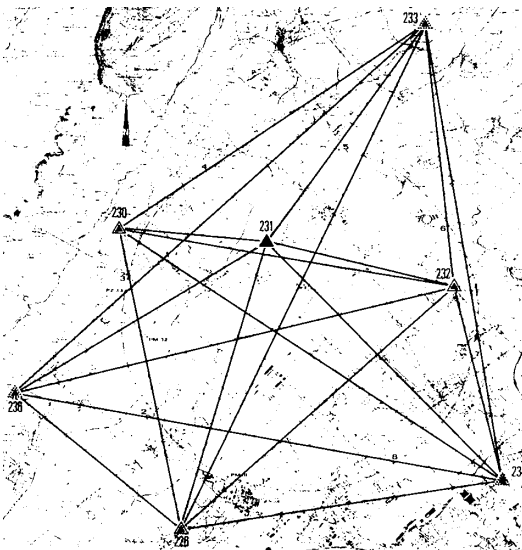


Fig. 29 LEP surface network

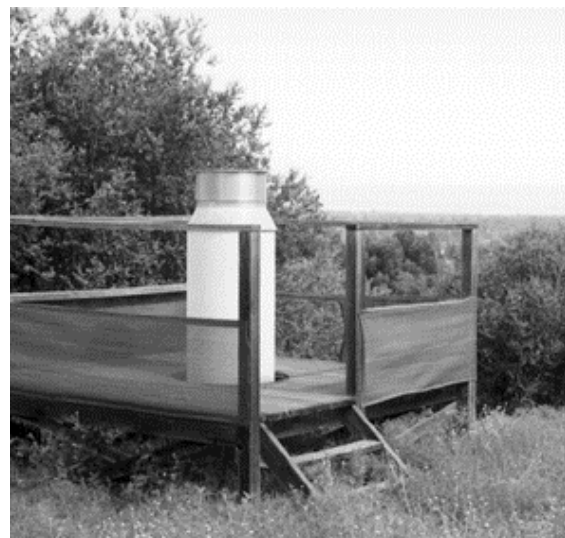


Fig. 30 Monument pillar

Using state-of-the-art equipment in a small trilateration network with good intervisibility of monuments can yield standard deviations for the horizontal coordinates in the range of 2 mm + 1 ppm. In medium size applications it has been shown that GPS, combined with terrestrial observations and careful control of the antenna eccentricities (GPS, too, has its fiducialization problems), can yield positional accuracies of about 2 mm [10]. In large projects, like the SSC or LEP, positional accuracies of about 10 mm can be achieved using two-frequency GPS receivers. Trigonometric and differential levelling are the only accurate methods to determine elevations; both methods yield the same accuracies—approximately 1 mm for networks smaller than 2 km, and 20 mm for a SSC size network.

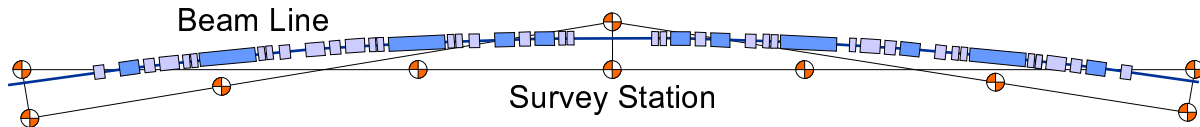


Fig. 31 Tunnel network

Tunnel Tunnel networks are usually long and narrow (see Fig. 31), and incorporate points beneath the shafts as connections to the surface net. The monument system can be 2-D (horizontal only) or 3-D: common designs are the SLAC 2-D marks, the DESY-HERA 3-D reference cups or the standard 1.5-inch floor cups and magnet mounts (see Fig. 11 in Section 2.3.2). Some kind of tripod or column-like monopod is used for the instrument set-up. The SLAC set-up (see Fig. 32) is designed to accommodate slopes of up to 15°; the HERA design is more optimised towards efficiency, virtually eliminating the task of centering instruments and targets over monuments (see Fig. 33) [11]. The elevation of the instrument above the 3-D reference cup is known very accurately, which facilitates 3-D mapping with theodolites. Both set-up types are forced centered over known points. Laser tracker and the more recent generation of Total Stations allow the efficient use of the free-stationing method (see Fig. 34).



Fig. 32 SLAC instrument set-up



Fig. 33 HERA instrument set-up

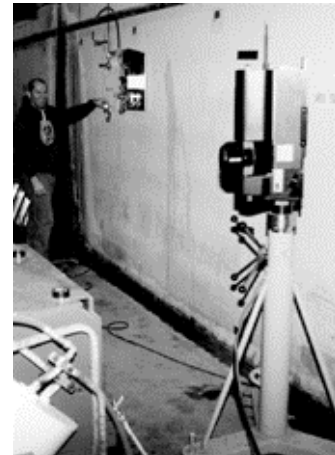


Fig. 34 Free-stationed laser tracker

4. FIDUCIALIZATION

Fiducialization is a fancy name for relating the effective electromagnetic axes of components to some kind of mark which can be seen or touched by instruments. The beam, influenced only by the electromagnetic field of a component, knows nothing about fiducials.

It is therefore of at least the same importance to accurately relate the magnetic axis to the fiducial marks as to correctly position the marks to their nominal coordinates. The term fiducialization is commonly also used to describe the task of relating the axis of mechanical components to their marks. These marks are then aligned to the nominal positions calculated with the information described in the previous chapters.

Fiducialization is a two step process: firstly, the axis of the component is determined, and secondly, the axis position is related to the fiducials.

4.1 Determination of centreline

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 reference for external alignment fiducials. This practice assumes that the magnetic field is well defined by the poles. However, this fails in the presence of saturation and in the case of superconducting magnets, which have no tangible poles. There are other well-known difficulties: the poles of an iron magnet are never perfectly flat or parallel. Where is then the magnetic mid-plane [12]? The equivalent problem for quadrupoles 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 centreline really is.

While without a doubt the electro-magnetic determination of the centreline is the most accurate method, quite often, budgetary, time, or other constraints make it necessary to rely on mechanical means.

4.1.1 Mechanical representation of axis

Design dimensions Magnets are often constructed from stacked laminations, what guarantees very repeatable dimensions. This permits the design of features into the shape of the laminations, which have a known and accurate relationship to the mechanical axis. Most commonly, these features have the shape of grooves or edges (see Fig. 2 above). As already described in Section 2.1.1, these features can be used to reference fixtures with targets, which then in turn will represent the centreline.

Bore target and mandrel If magnets could be machined perfectly, a bore target (see Fig. 35) in the shape of a short cylinder with the nominal bore diameter would touch all four poles of a quadrupole. Since these required tolerances can hardly be achieved with affordable fabrication methods, the target is likely to touch only three of the poles. This method is therefore limited to lower accuracy applications, unless the typical method is modified. This improvement is accomplished by moving the target in the bore such that the target sequentially references different sets of poles. These four target positions, in case of a quadrupole, describe a circle. The centre of this circle references the mechanical axis.

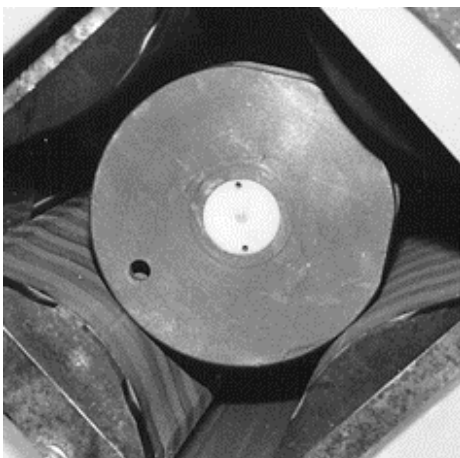


Fig. 35 Bore target



Fig. 36 Mandrel in magnet

A mandrel (see Fig. 36) is a combination of two bore targets on a common mechanical axis. Inserted into a quadrupole, it references and represents the mechanical axis. But, as before with the bore target, fabrication limitations will cause the mandrel only to touch three poles at two longitudinal locations. Moving the mandrel in the same manner as the bore target will alleviate the problem.

Scanning of poles The bore target and mandrel will always pick-up the highest point of a pole. Therefore, stacking imperfections or remaining burrs will bias the measurement. This can be avoided by scanning the cross section of each pole in combination with a shape least squares fit

(see Fig. 37) [13]. In most cases circle shape fits are sufficient, otherwise hyperbolic or parabolic shapes can be fitted. A subsequent circle fit through the centres or focal points of the previous pole shape fits will reference the axis location at the cross section longitude. If this process is repeated at more than two cross sections, a line fit will further reduce determination errors. The scanning operation is best accomplished on a Coordinate Measurement Machine (CMM); however, if the magnet's dimensions or weight exceed the available measurement or loading capacity, theodolite measurement system or laser tracker measurements will suffice.

4.1.2 Electro-magnetic axis determination

The inherent problems of approximating the magnetic axis of a component with its mechanically determined centreline can be avoided by direct magnetic measurements. Several methods are available using various properties of the magnetic field. Properties commonly used are the magnetic field's symmetries and its lack of radial field in the centre [14]. The following is only intended as a listing of applicable methods [15], technical details are given elsewhere.

Rotating coil A multipole magnet field will induce a voltage, which is cancelled by the symmetry of the coil. The output voltage of the coil is proportional to the magnitude of the dipole field, which is only a function of distance from the magnetic centre.

Vibrating wire A light wire is tensioned by a weight at one end such that its lowest resonant frequency is around 50 Hz. Shaken in either the vertical or horizontal plane, the voltage induced in a loop containing the wire is observed, and minimised by moving its ends. At minimum first harmonic output, the wire will be along a family of lines, all of whom intersect at the nodal point of the magnet [16].

Taut wire This method uses the property of zero field at the centre. After the magnet is energised, a current is passed through the wire. If the wire is not at the magnetic centre, a deflection will be observed. The wire position is then corrected, and the process repeated until no deflection of the wire is observed when the wire current is turned on [17].

Ferrofluidic cell Ferrofluidic cells are a means to make the virtual magnetic axis visible. The physical mechanism of this method is based on the scattering of polarised light on aligned colloidal particles in multipole fields [18]. A target with the fluid is placed in the bore. White plane-polarised light is shone through the solution from one end of the magnet. From the other end, an observer looks at the target through a plane-polarising analyser. The analyser is aligned with the polarise of the incoming light such that complete cancellation of light should occur when the magnet is turned off. With magnetic field, complete cancellation does not occur except along two perpendicular axes, which cross at the magnetic centre of the quadrupole [19].

4.1.3 Electrical axis

Some diagnostic instruments need to be accurately positioned. E.g., the relationship between a beam position monitor (BPM) and its related quadrupole/ sextupole often needs to be known to high precision. This requires fiducializing the BPM accurately. To determine the

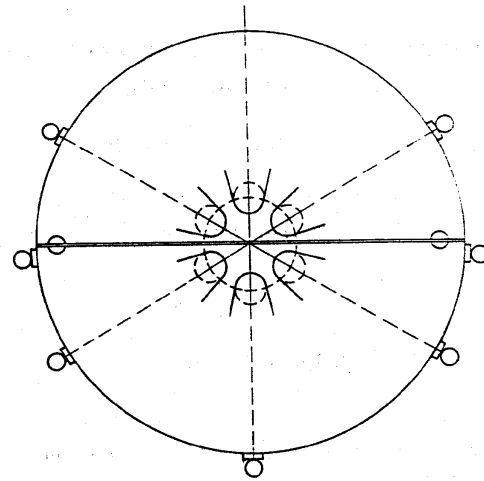


Fig. 37 CMM supported pole scans

electrical centre of a BPM, a fast pulse is sent down a wire stretched through the BPM, and its position is sensed with the same electronics used to measure the beam position [20].

4.2 Relating axis to fiducials

The above-described methods will visualise the mechanical or magnetic axis by optical targets or by a wire. While optical instruments can acquire targets directly, a wire-represented axis requires an additional transfer to marks, which can be acquired by survey instrumentation.

4.2.1 Referencing a wire

Jigs are commonly used to reference a wire to physical marks. The wire can be related to a jig using capacitive sensors, laser scanning [21], or microscopes [22]. These measurements combined with the jig's dimensions will reference the wire position to the jig's fiducials.

4.2.2 Transfer of axis to component fiducials

Fixturing An example for this method is the Danfysik measurement stand (see Fig. 38, 39), which is a commercial version of a measurement bench developed for LEP at CERN [23]. As a result of the measurement process, two CERN socket-type fiducials are mechanically adjusted to be precisely in the same vertical plane as the magnetic axes. The measurement bench automatically centres a quadrupole onto its rotating coil, which represents the magnet's magnetic axis. A fixture positions a laser beam above the magnet in exactly the vertical plane of the coil at a given vertical offset. The laser acts on a quadrant detector, which is mounted inside a 3.5-inch sphere, which in turn is placed sequentially into the two CERN socket base plates. Each base plate is now manually adjusted such that the quadrant detector readings become zero. The z-coordinate of the base plates is provided by mounting references.

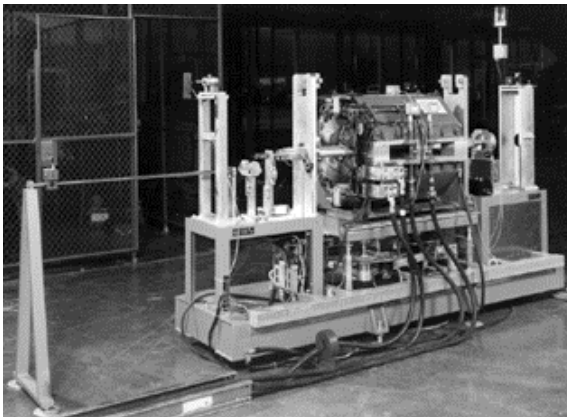


Fig. 38 Danfysik rotating coil bench

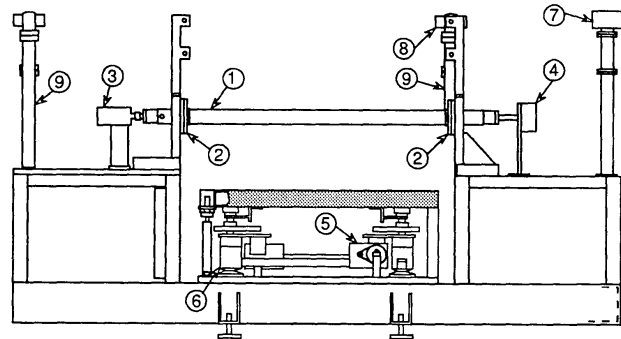


Fig. 39 Side view of bench. Rotating coil assembly consisting of measurement cylinder (1), air bearings (2), DC motor (3), and angular encoder (4). Magnet positioning system consisting of magnet platform, horizontal movement gears and motors (5), vertical movement gears and motors (6). Alignment system consisting of laser (7), photo detector with Taylor Hobson ball (8), and calibration supports (9).

Optical tooling Optical tooling is the standard method at SLAC to reference a bore target or rotating coil to the magnet's fiducials (see Fig. 40 – 42) [24]. The magnet is first levelled using observations to the split planes or to clean laminations. A transit is then “bucked-in” parallel to the magnet by measuring offsets to the iron or laminations, representing the magnet's z-coordinate axis. A second transit is set-up parallel to the line-of-sight of first transit such that the range of its telescope micrometer includes the axis of the magnet. The offset amount is determined by simultaneously reading a common scale-bar with both transits. The second transit's crosshairs are brought into coincidence with the bore or rotating coil target mark by adjusting the parallel plate micrometer. Subsequently, the micrometer is read, and the reading is added to the transit offset value. As a result, the horizontal offset between the master transit and the magnet's axis is known. This value is transferred onto the fiducials by touching these fiducials with scales held perpendicular to the line-of-sight of the master transit and then reading the individual fiducials' offsets with the master transit. Adding these offsets to the previously determined axis-transit offset will reference the fiducials to the axis. To determine the z-coordinate of the fiducials, a third transit is set-up perpendicular to the line-of-sight of the master transit by collimation of its trunion mirror. Scale readings perpendicular to the line-of-sight of the third transit will yield z-offset of the fiducials. To reference these z-offsets to the magnet iron, readings to the front and back face of the magnet are also taken. The vertical component is determined by standard levelling techniques. Combining all these values produces fiducial coordinates in reference to the axis.

Theodolite Measurement Systems (TMS) Measuring horizontal and vertical directions from at least two stations to the same target, after the relative orientation of the stations has been determined, is sufficient information to calculate 3-D coordinates of that target (see Fig. 43). The model volume can be extended by adding more theodolites or by moving one theodolite to a new station. However, a minimum of three common points needs to be measured from each station. Following these rules, it is straightforward to measure the fiducial and the axis targets coordinates. TMSs are significantly more efficient and tend to produce more reliable coordinates than optical tooling.

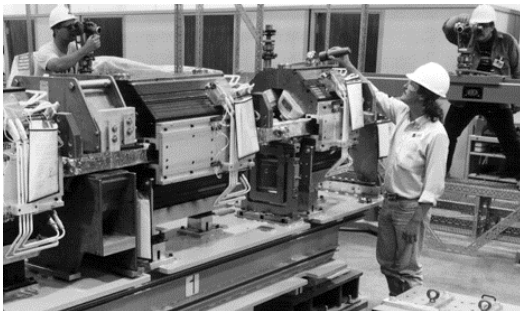
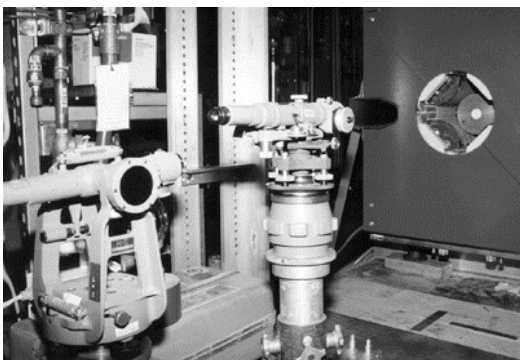


Fig. 41 Optical instruments and bore target

Fig. 40 Optical tooling from tooling bars



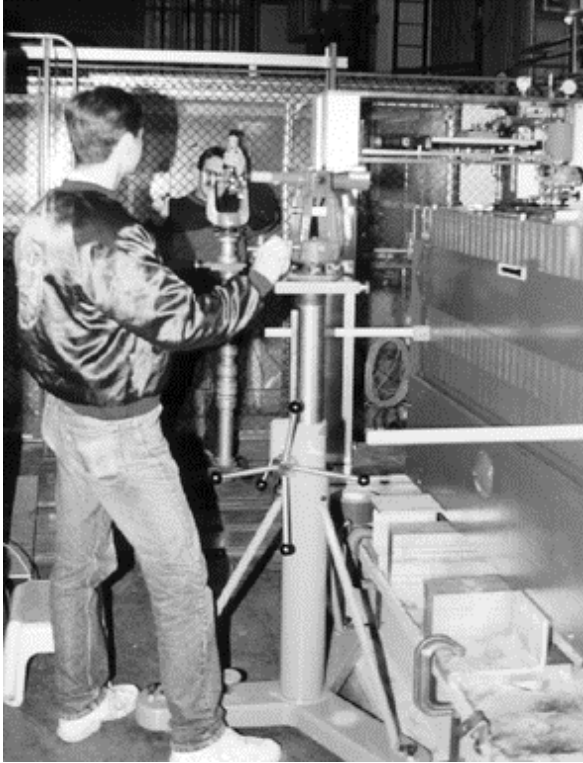


Fig. 42 Autocollimating two transits

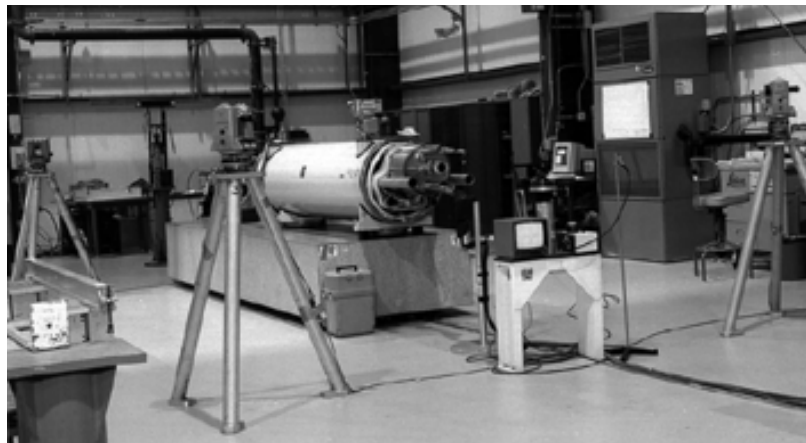


Fig. 43 Theodolite Measurement System set-up

Polar measurements Laser trackers (see Fig. 44) [25] and total stations measure not only horizontal and vertical directions, but also distances with respect to the same origin. This fact allows one to calculate 3-D coordinates using measurements from only one station. Polarly determined coordinates with laser trackers are in the same accuracy domain as TMS results. Total station (TC2002, TDM5000) based measurements are somewhat less accurate. However, the polar technique can provide an up to 300% productivity advantage over TMS procedures.

Coordinate Measurement Machine (CMM) measurements CMMs can address targets either optically or mechanically. They are available in a wide range of measurement volumes and accuracy capabilities. Because CMMs measure coordinate differences directly, they represent the most efficient approach and can also reach much higher accuracies (see Fig. 45).



Fig. 44 Laser tracker SMX 4000

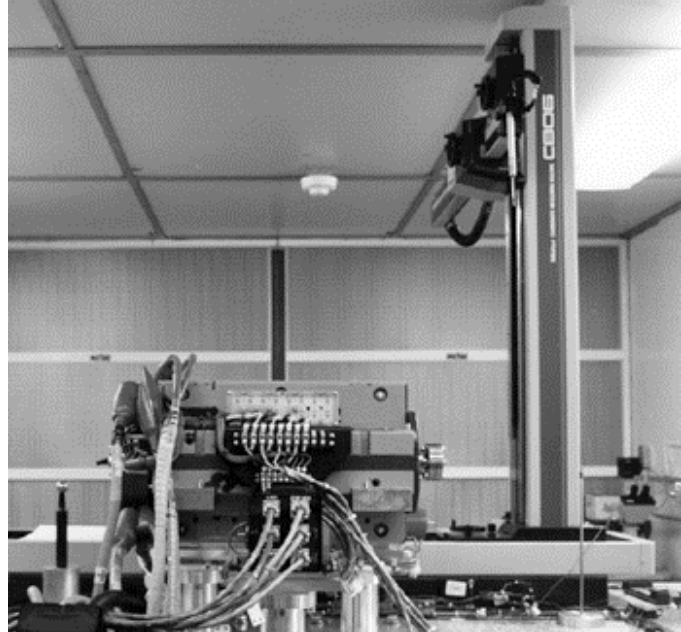


Fig. 45 Magnet fiducialization with CMM

5. SUPERCONDUCTING MAGNET FIDUCIALIZATION MONITORING

Superconducting magnets don't have poles like a traditional warm magnet (see Fig. 46). The field is generated by a coil, which is maintained by collars and located at the centre of an iron yoke. Since there is very little iron, the axis of the field is determined by the position and shape of the coil, which itself is not geometrically stable [26]. It is therefore not possible to fiducialize the magnet in reference to the mechanical axis of the yoke. The coil and yoke, referred to as the cold mass, are insulated from the ambient temperature by heat shields. This assembly is inserted into a steel cylinder, which also provides the structural support. The situation is compounded by the fact that the cold mass is submitted to high temperature differentials during cool down. The cold mass supports need to provide stable support while at the same time permitting a longitudinal expansion/contraction in the order of several centimetre. This not only makes the cryostat the cold mass inaccessible, but the above design criteria make the cold mass to cryostat relationship mechanically unstable. Consequently, "we have to align an object that we can neither see nor touch directly" [27].

Because of these boundary conditions, precise fiducialization of superconducting magnets requires a determination of their magnetic centreline with one of the above mentioned methods at superconducting temperatures. The execution of these measurements is more involved than the axis determination of a warm magnet. Firstly, a superconducting magnet can only be cooled down if the vacuum chamber is under vacuum. Since it would be too difficult to install the magnetic measurement equipment inside a vacuum vessel, a secondary pipe is usually inserted into the vacuum chamber and sealed vacuum tight to the chamber. Secondly, since the cold mass is inaccessible, fiducials can only be attached to the cryostat, which does not have a stable relationship to the cold mass. Therefore, the fiducialization must be supported by a determination of the possible variations in the cold mass to cryostat relationship.

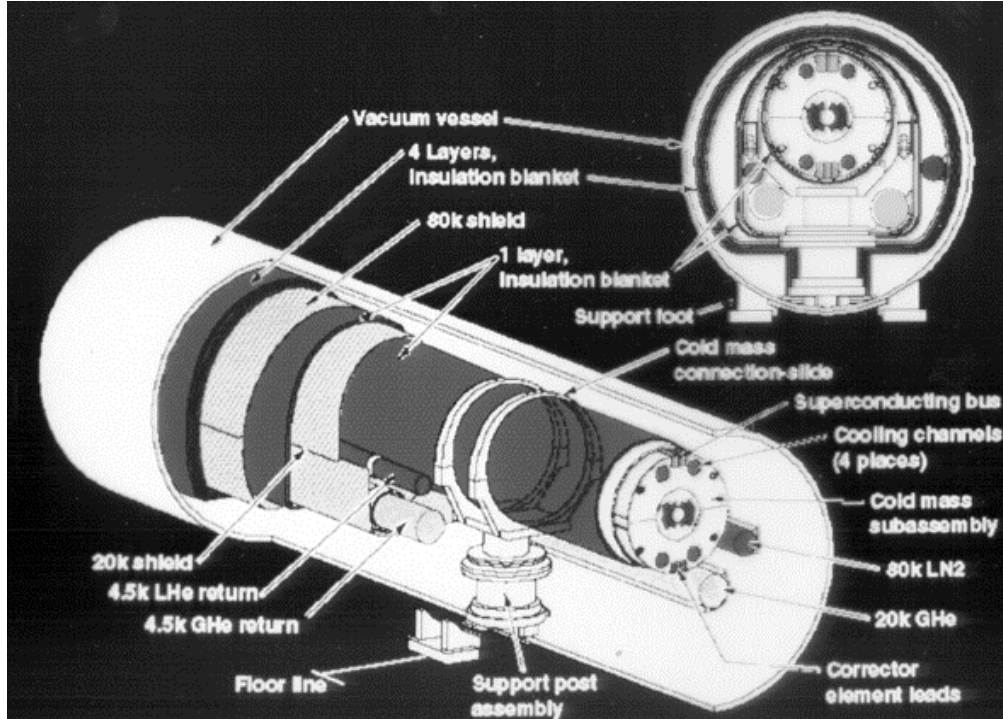


Fig. 46 SSC Superconducting magnet schematic

5.1 LHC magnets

Some magnets of the LHC string test set-up have been equipped with a monitoring system. Inside a cold mass support-foot a short silica rod is attached to the cold mass (see Fig. 47). The position of the rod is monitored in all degrees of freedom by capacitive sensors with respect to the cryostat. The sensors are capable of resolving μm size motion. First results indicate that the feet move as expected in the longitudinal direction, are less stable than expected in the vertical direction, and do not move in the perpendicular direction [28].

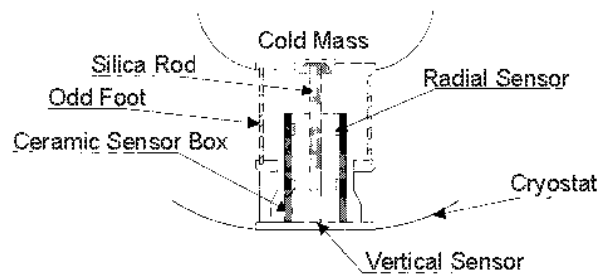


Fig. 47 LHC magnet cold mass monitoring system

5.2 SSC

A test plan was developed to establish cold/warm relationships for SSC dipole and quadrupole magnets by making direct autocollimation and autoreflection measurements through windows to the cold mass (see Fig. 48, 49). The mechanical design was composed of a clear optical window in the vacuum vessel, an optically coated window in the 80K shield, a through hole in the 20K shield and autocollimation mirrors and targets attached to the cold mass. Four locations at two axial stations on the magnet were instrumented this way. The resulting heat leaks were deemed acceptable for R&D magnets, but would not have been accepted for production magnets. First measurements on one magnet showed the cold mass arching and moving by about 0.1 mm in the horizontal plane, a negative vertical translation of about 0.7 mm and inconclusive roll changes [29].

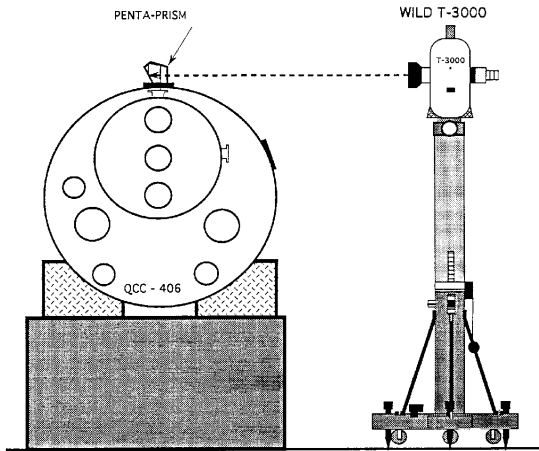


Fig. 48 Sketch of horizontal shift monitoring



Fig. 49 Vertical shift observation

6. CASE STUDIES

The following are short descriptions of actual “setting reference targets” projects, which are exemplary for many future applications.

6.1 Warm magnets

6.1.1 FFTB magnets

The Final Focus Test Beam (FFTB) is a transport line designed to test both concepts and advanced technologies for application to future linear colliders. In order to achieve the desired spot sizes at the focal point ($\sigma_x = 1 \mu\text{m}$, $\sigma_y = 60 \text{ nm}$) among others, demanding tolerances on alignment ($\sigma_x = 100 \mu\text{m}$, $\sigma_y = 60 \mu\text{m}$) must be met. To retain as much as possible of this tight error budget for the alignment process, a very accurate magnet fiducialization bench based on the vibrating wire technique was developed (see Fig. 50). Magnetic centre location was accomplished by placing the wire at six different small angles ($< 1 \text{ mrad}$) with respect to the magnet axis, zeroing the first harmonic electromotive force signal each time. The spatial location of the wire was first detected with a modified tooling microscope. Then it was transferred from the microscope to fiducials by means of a coordinate measurement machine. The resultant six lines were used to find the point at which the average distance from the point to each of the lines was minimised. The fitting would produce a centre unconstrained by any mechanical reference to the magnet (see Fig. 51). The RMS deviation of any line from the point of closest approach was less than $4 \mu\text{m}$ relative to the external fiducials of the magnet.

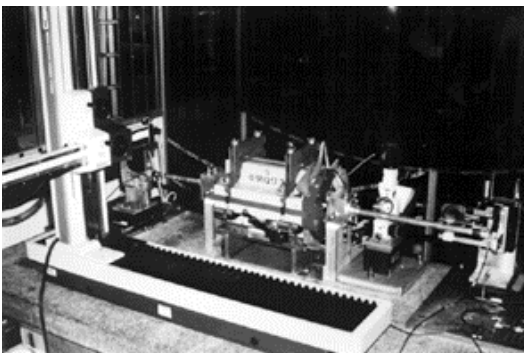


Fig. 50 FFTB magnetic measurement bench

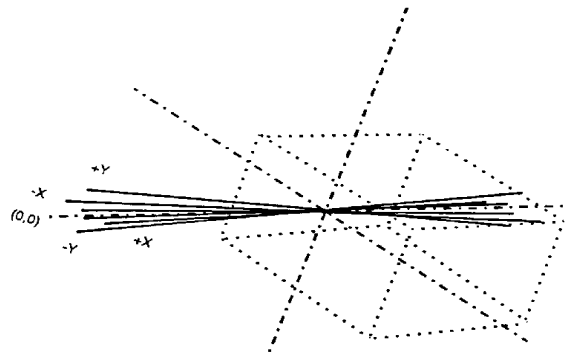


Fig. 51 Intersecting wire lines

6.1.2 PEP-II quadrupoles

The High Energy Ring (HER) of the PEP-II project re-uses about 280 of the original PEP quadrupoles. The original PEP survey concept provided fixtures to reference the mechanical axis to fiducials. While changing the fixture design, the principle concept was retained. However, when verifying fixture functionality on test magnets, problems were encountered. An investigation traced the reference problems to dimension variations of the magnets. The quadrupoles are assembled from four quadrants that are individually stacked from laminations. Although dowel pins referenced the assembly, forces were introduced in the assembly process, which twisted the magnets sufficiently to invalidate the fixture to axis relationship. Subsequently, all 280 quadrupoles were mechanically fiducialized. A mandrel (see Fig. 52) was inserted into the bore and placed into four positions (see Fig. 53) such that all pole combinations were used. The same process was repeated with the mandrel shifted longitudinally by a small amount to eliminate burr or stacking biases. In each position the two end points of the mandrel were measured with a laser tracker (see Fig. 54). The laser tracker also swept the fiducials and floor control points from stations. Variations of up to half a millimetre were identified.

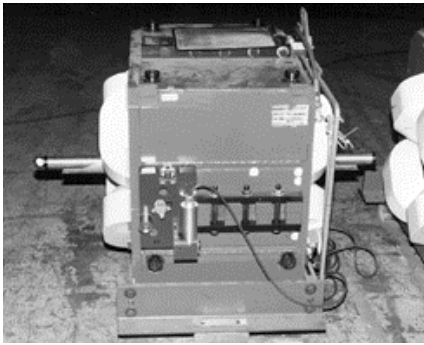


Fig. 52 Mandrel inserted in bore

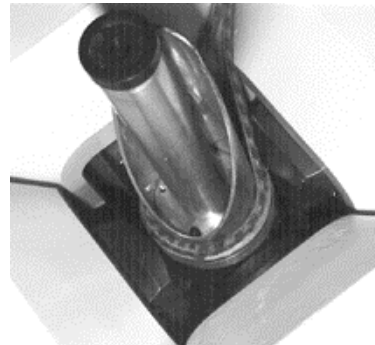


Fig. 53 Mandrel referencing upper two poles



Fig. 54 Fiducialization with laser tracker

6.2 Superconducting magnets

6.2.1 RHIC

A magneto-optical procedure was designed, to directly locate the null-field axis with respect to outside fiducial reference points of the magnet assemblies. The procedure has been used to determine the null axis, both when the magnet assembly was at room temperature, and

after cooling to 4° K. All of the arc CQS assemblies are measured at room temperature. A subset of these assemblies were also measured at liquid helium temperature, to obtain statistics on the null axis' position shift caused by differential thermal contraction of magnet parts between these temperatures [30].

The magnetic measurement procedure is based on ferrofluidic cell measurements. The cell is placed in the magnet bore on a rail support and illuminated with collimated light (see Fig. 55), which passes through a polarising filter. The cell (see Fig. 56) is observed with an alignment telescope (see Fig. 57) through a polarising filter. The telescope is set-up such that its line-of-sight is close to the geometric axis. Two 3.5 inch target spheres on either side of the magnet are adjusted to the boresight. These spheres can later be observed by a TMS, which facilitates the spatial reference to external fiducials. Prior to energising the magnet, the polarises are crossed to give a sharp extinction of the light beam. When the magnet is energised, a characteristic cross shadow pattern is seen, being centrally symmetric about the magnetic axis (see Fig. 58). Vertical and horizontal components of the axis' displacements from the previously established boresight are measured directly using the plane plate micrometers built into the alignment telescope. The procedure was automated by attaching a CCD camera to the telescope and replacing the micrometer reading with image processing [31].

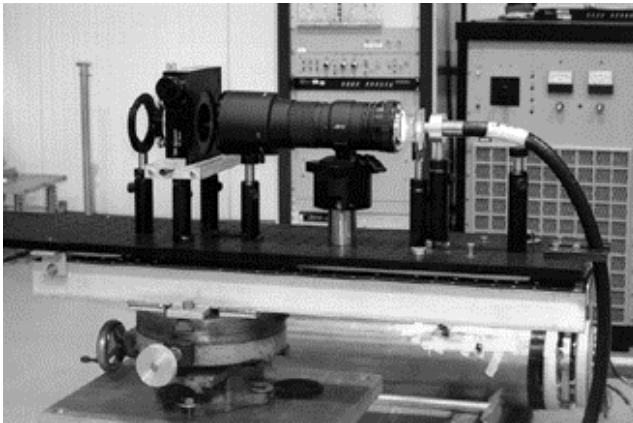


Fig. 55 Collimated light source and polarising filter

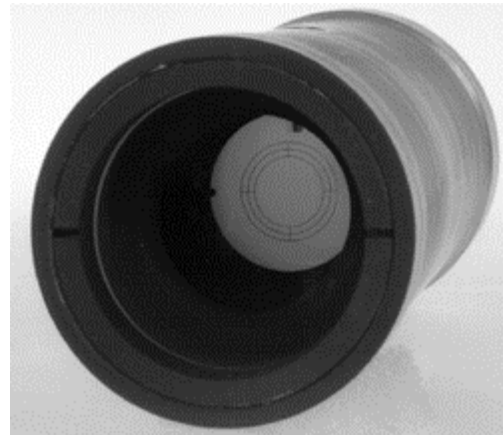


Fig. 56 Ferrofluidic cell target

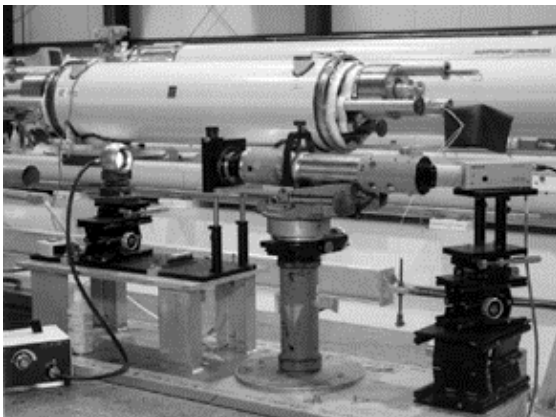


Fig. 57 Telescope with CCD camera and filter

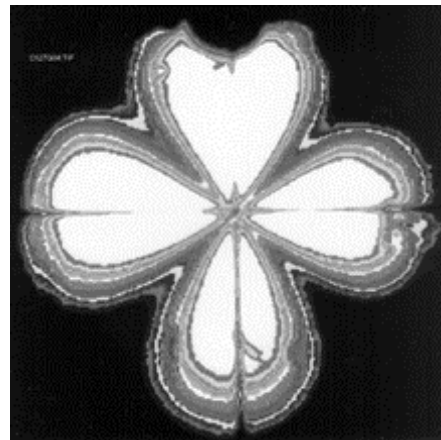


Fig. 58 Colloidal target pattern

6.2.2 CEBAF cavities

The CEBAF accelerators are powered by superconducting cavities. A cavity pair is mounted in a cryounit. Four cryounits are housed in one cryomodule. The internal alignment is specified to 0.5 mm in the horizontal and vertical plane and 0.5 mrad roll. After the cavities leave the chemical preparation, they are assembled on an alignment stand into pairs inside a class 100 clean room (see Fig. 59). Subsequently, four pairs are mounted in a helium vessel within an insulated dewar flask. To maintain the relative pair alignment, the cavity pair with its alignment fixture is slid on bearings riding on precision rods through the open vessel. Subsequently, the cavities are connected to the helium vessel, which after removal of the alignment fixture retains the pair alignment. The beam pipe is installed which will become the fiducial. Afterwards, the magnetic and thermal shielding is added, and then the unit is inserted into the vacuum vessel. The vacuum vessel is supported through a pair of Thompson rods and bearings. Nitronic rods are installed which support and axially restrain the helium vessel inside the vacuum vessel. Adjustments of the rods align the mounted pair inside the cryounit. Alignment has now been transferred outside the vessel to the two beam flanges and is maintained by the fixturing of the Thompson rail and bearings. The integration of four cryounits into one cryomodule is carried out on a precision assembly bench. From a line parallel to the axis of the module, offsets are measured to the cryounits' flanges. Instead of reading scales, special offset bars of defined length with crosshair targets at the end are used (see Fig. 60). When all cross hairs line up on the reference line, the cryounits are in good relative alignment. Typical alignment is reported to be better than 0.25 mm and 1.25 mrad [32].

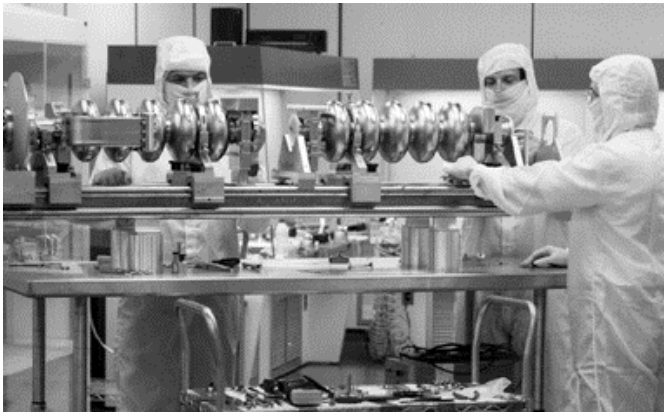


Fig. 59 Assembling two cavities into one cryounit

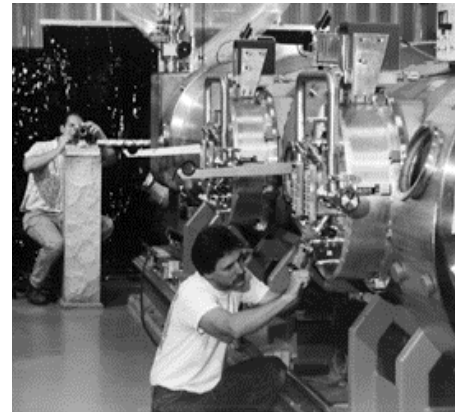


Fig. 60 Aligning the cryounits in a cryomodule

6.2.3 HERA magnets

The HERA superconducting magnets have been equipped with two active fiducials each, i.e. so that not only targets but also instruments can be referenced to their axes (see Figs. 61, 62). The fabrication dimensions are checked on an optical test stand. On either side of the magnet two columns are set-up. Each column carries two optical tooling base plates with a horizontal spacing equivalent to the distance between the nominal magnet axis and the fiducial. Two alignment telescopes are set-up on one side (see Fig. 63) looking at Taylor Hobson spheres on the opposite column. Then the magnet's fiducials are aligned to the line defined by the one telescope and its target, and at the same time, the magnet's roll is adjusted. The second telescope target combination now represents the nominal axis of the magnet. Sliding a self-centering target through the bore, horizontal and vertical deviations can be

measured (see Fig. 64). A stretched wire system is afterwards used to confirm the magnet axis' position in a cooled down condition. There, the wire replaces the boresight equipment. By measuring the spatial relationship of the wire and the fiducial line-of-sight, the magnetic axis is referenced to the fiducials.

7. CONCLUSION

It should have become apparent that alignment targets are an intrinsic part of any accelerator. Even small machines cannot be installed and maintained without some kind of reference to the design coordinate system and the path of the particles. The choice of the targeting is directly correlated to positioning methodology and instrumentation, and therefore lastly to alignment cost. May our magnets always be aligned!

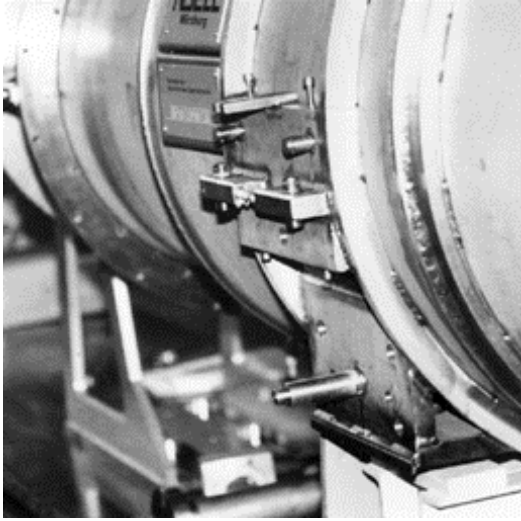


Fig. 61 Hinges for fiducial platform

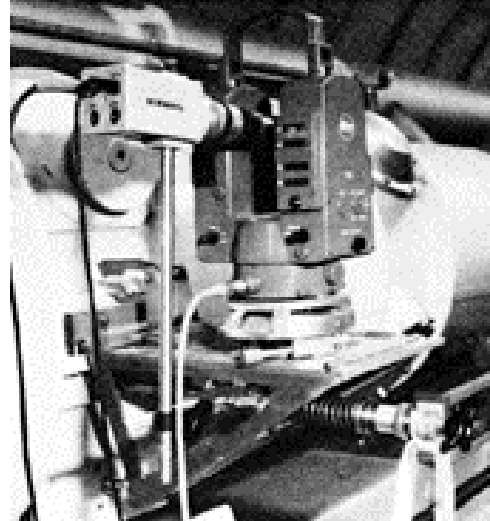


Fig. 62 Fiducial platform

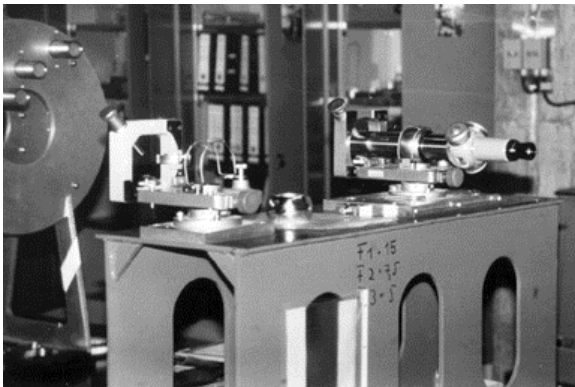


Fig. 63 Pedestal with telescopes

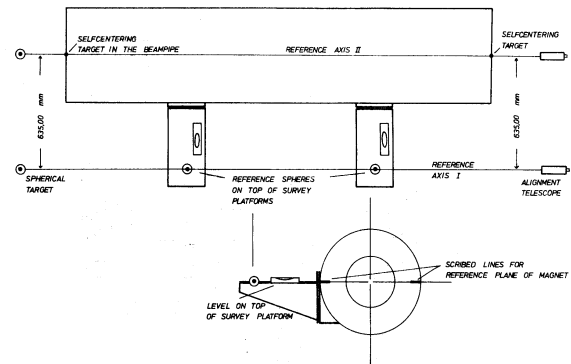


Fig. 64 Sketch of fiducialization geometry

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REFERENCES

- [1] H. Grote and F. Christoph Iselin, *The MAD Program – User Reference Manual Vers. 8.1*, Geneva, Switzerland, 1991, p. 1, CERN/SL/90-13 (AP) Rev. 2
- [2] Karl Brown et. al., *TRANSPORT – A Computer Program for Designing of Charged Particle Beam Transport Systems*, CERN 73-16, revised as CERN 80-4, CERN, 1980
- [3] Bernd Wand, *Stanford Linear Collider Magnet Positioning*, SLAC-Pub-5640, Stanford, 1991
- [4] John E. Jackson, *Sphere, Spheroid and Projections for Surveyors*, (Granada, London 1980), p. xi; Vaníček, Petr and Krakiwsky, E., *Geodesy—The Concepts*, (Elsevier, Amsterdam, 1986), pp. 1–8, 110.
- [5] Jackson, *op. cit.*, p. 84.

- [6] Alfred Leick, *GPS Satellite Surveying*, John Wiley & Sons, New York, 1990, p. 188.
- [7] W. Gurtner and Beat Bürkli, *Deviation of the Vertical*, in: Applied Geodesy for Particle Accelerators - CERN Accelerator School 1986, Geneva, 1997, p. 116, CERN 87-01
- [8] Jackson, *op. cit.*, p. 84.
- [9] Clyde C. Goad, Precise Positioning with the GPS, in: Applied Geodesy for Particle Accelerators, CERN Accelerator School, CERN 87-01, Geneva, 1987, p. 36ff.
- [10] R. Ruland and A. Leick, *Application of GPS in a High Precision Engineering Survey Network*, in: Proc. First Symp. on Precision Positioning with GPS, Rockville, MD, 1985, p. 483ff.
- [11] Franz Löffler and W. Schwarz, *The Geodetic Approach for HERA*, in: Proc. of the First Int. Workshop on Accelerator Alignment, Stanford, 1989, SLAC-375, p. 117.
- [12] Alex Harvey, *The Magnet Fiducialization Problem*, in: Proc. Of the First International Workshop on Accelerator Alignment, Stanford, 1989, SLAC 375, p. 200
- [13] H. Friedsam et al., *Magnet Fiducialization with Coordinate Measurement Machines*, in: Proc. Of the First International Workshop on Accelerator Alignment, Stanford, 1989, pp. 206ff
- [14] J.K. Cobb and J.J. Muray, *Magnetic Center Location in Multipole Fields*, Nuclear Instruments and Methods, North-Holland Publishing Co., Vol. 46, 1967, p. 99
- [15] Some more exotic methods are not mentioned, see: John Warren, *Evaluation of the Concept of Gamma Ray Scanner for Magnet Alignment*, SSC Internal Report, unpublished; Lee Griffith, *Locating the Magnetic Centerline with a Low Energy Electron Probe*, in: Proc. of the First Int. Workshop on Accelerator Alignment, Stanford, 1989, SLAC-375, pp. 223ff.
- [16] G.E. Fischer, R.E. Ruland et al., *Precision Fiducialization of Transport Components*, in: Proc. Of the 3rd European Particle Accelerator Conference, Berlin, 1992, SLAC-Pub 5764
- [17] Cliff Fortgang, *Taut Wire Alignment of Multipole Permanent Magnet Quadrupoles*, Invited talk presented at the 6th International Magnetic Measurements Workshop, LBL, 1989
- [18] J.J. Muray, *Magnetic Field Measurement and Spectroscopy in Multipole Fields*, Journal of Applied Optics, Vol. 4, 1965, p. 1011
- [19] J.K. Cobb and J.J. Muray, *ibid*, p. 99
- [20] R.E. Ruland and G.E. Fischer, *The proposed Alignment System for the Final Focus Test Beam at SLAC*, in: : Proc. of the Second International Workshop on Accelerator Alignment, Hamburg, 1990, p. 441, SLAC-Pub 5326

- [21] Daryl W. Preston and Roger W. Warren, *Wiggler Field Measurements and Corrections Using the Pulsed Wire Technique*, in Proc. of the 13th Int. Free Electron Laser Conf., Santa Fe, 1991
- [22] Steve Williams, *Magnet and BPM Measurements*, in: Proc. of Final Focus Test Beam Collaboration Meeting, SLAC, 1993
- [23] O. Pagano et al., *A Highly Automated Measuring System for the LEP Magnetic Lenses*, in: Journal de Physique, Vol. 45, 1984, p. C1-949
- [24] Basically, transits are used to set-up a rectangular coordinate system. This is facilitated by auto-collimating a second transit to a mirror which is mounted on the trunion axis of the master transit truly perpendicular to its optical axis. Scales, referencing a feature and held perpendicular to a line-of-sight, are read with the assistance of the plane plate micrometer. A transit in its geometry is very similar to a theodolite. However, an optical tooling transit usually does not have angle measurement capabilities. Its telescope is tuned to the predominantly short line-of-sights. Accordingly, it provides excellent line-of-sight stability and has a built in plane plate micrometer.
- [25] Robert Ruland, *The Chesapeake Laser Tracker in Industrial Metrology*, in Proc. of the Third International Workshop on Accelerator Alignment, Annecy, CERN Pub., 1993, pp. 101ff
- [26] J. Gareyte, *Future Hadron Colliders*, CERN Accelerator School, Noordwijkerhout, Netherlands, 1992, CERN 92-01
- [27] E. Menant and J.-P. Quesnel, *Reference Target Positioning*, in: Proc. of CERN Accelerator School Magnetic Measurement and Alignment, Montreux, 1992, p. 335, CERN 92-05
- [28] D. Missian, *Metrology of Superconducting Magnets*, in Proc. of the Fourth International Workshop on Accelerator Alignment, KEK - Tsukuba, KEK Proc. 95-12, 1996, p. 231
- [29] C. Corbet, et.al., *Optical Measurements of SSC Arc Quadrupole Cold Mass Location*, unpublished
- [30] Michael Goldman et al., *Optical Fiducialization of Multipole Magnets for the Relativistic Heavy Ion Collider*, in preparation
- [31] Michael Goldman, *Checkout Procedures and Tests for Magneto-Optical Measurements of CQS Magnets using Colloidal Cells*, Brookhaven National Laboratory, 1995, unpublished
- [32] W.J. Scheider, et al., *Alignment of CEBAF Cryomodules*, in Proc. of the IEEE Particle Accelerator Conference, 1992, pp. 2929ff