Fiducialization Procedures for the ALS Ring Magnets and the Booster Synchrotron Girders

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Introduction

The Advanced Light Source (ALS), now under construction at Lawrence Berkeley Laboratory (LBL), is a synchrotron radiation source of the third generation designed to produce extremely bright photon beams in the UV and soft X-ray regions.[1] Its main accelerator components are a 1 - 1.9 GeV electron storage ring with 196.8 m circumference and 12 superperiods, a 1.5 GeV booster synchrotron with 75.0 m circumference and 4 superperiods, and a 50 MeV linac, both placed inside the storage ring. The storage ring has particularly tight positioning tolerances for lattice magnets and other components to assure the operational characteristics.

The general survey and alignment concept for the ALS booster and storage ring is described elsewhere in these proceedings.[2] It requires the lattice magnets to be installed onto girders (one for each storage ring superperiod and three for each booster superperiod) and aligned with respect to the girder coordinate system defined by the girder fiducials. Each girder is then installed and aligned to its required location defined in the accelerator coordinate system. The lattice magnets must be aligned in the booster and storage ring lattice with respect to the magnetic center of each element. In the case of the booster magnets, the offsets of the magnetic center to the mechanical center were less than the alignment tolerances, and the magnets are aligned with respect to the mechanical centers. In the case of the storage ring, the tight alignment tolerances require the correction of the fiducial data to the magnetic centers.

This paper describes the methods of measuring the location of the fiducial balls with respect to the magnet mechanical centers. For the storage ring magnets the paper covers the means of measuring the magnetic error multipoles and correcting the fiducial coordinates to compensate for the offset between the magnetic and mechanical centers with computations using the magnetic measurement data.

Magnet Coordinate System

The coordinates of the fiducials on each magnet are defined with respect to the local right hand (beam following) coordinate system of the magnet, u, v, w: w, in the beam direction; u, radially away from the ring center (to the left looking in the w direction); v, vertical; u', pitch; v', yaw; w', roll. The origin of the coordinate system is defined at the center of the magnet and is illustrated in Fig. 1.

Magnet alignment tolerances for the main booster and storage ring magnets are included in Table 1.

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Element	Number	Δw [mm]	Δu [mm]	Δv [mm]	Δu' [mrad]	Δv' [mrad]	Δw' [mrad]
STORAGE RING							
srB	36	0.15	0.15	0.15	./.	./.	0.25
srQD	24	0.30	0.15	0.15	./.	./.	0.50
srQF	24	0.30	0.15	0.15	./.	./.	0.50
srQFA	24	0.30	0.15	0.15	./.	./.	0.50
srSF	24	0.50	0.15	0.15	./.	./.	./.
srSD	24	0.50	0.15	0.15	./.	./.	./.
BOOSTER RING							
brB	24	0.50	0.30	0.30	1.0	1.0	1.0
brQD	16	0.50	0.30	0.30	1.0	2.0	1.0
brQF	16	0.50	0.30	0.30	1.0	2.0	1.0
brSF	10	1.0	1.0	1.0	2.0	2.0	2.0
brSD	10	1.0	1.0	1.0	2.0	2.0	2.0

Table 1. Magnet Alignment Tolerances

Mechanical Fiducialization of the Lattice Magnets

Each magnet carries four fiducial posts that are welded to its upper surface without attempting to achieve any precise positioning. Different exchangeable targets are used on these posts, either optical targets with an engraved circle and center point on a tilted plane for surveying or tooling balls for alignment measurement in combination with dial indicators or other probes (Fig. 2). The mechanical location of tooling balls, installed in each fiducial post, is measured in three dimensions using the coordinate system of the measuring device. These measured coordinates are then transformed to the “mechanical” (u,v,w) coordinate system of the magnet, with its origin at the mechanical center of each magnet.

The mechanical coordinate system of each magnet is defined with respect to the mechanical features of the core. The cores for each magnet are made from precision stamped laminations and the upper surfaces of assembled magnets and parting planes of two and three piece magnets are precisely parallel to the central axis of the magnet. Moreover, great care is taken in assembling the core segments so that the axes of each core segment are precisely normal to the planes of the laminations. Thus, the u/w plane (defining u’ and w’, the pitch and roll) of the magnet is determined from the upper plane of the assembled core or the parting plane of a core segment.

Storage Ring Sextupole (srSF and srSD)

The measurements of the fiducial balls, installed in the fiducial posts, for the srSF and srSD sextupole upper core segments were performed in a coordinate measuring machine (CMM) provided by an outside vendor.[3] A fixture was made for mounting the assembled core segment on the CMM bed (Fig. 3). This fixture established the mechanical vertical w/v plane direction for the core segment. A cylinder, machined to the pole radius of the magnet, was used to provide u=0 and v=0 datums for the fiducial measurements. The longitudinal mechanical center was determined by establishing the position of the core midplane by measuring the w coordinate of both ends of both poles in the core segment.

Storage Ring Quadrupoles (srQF, srQD and srQFA)

The measurements of the location of the fiducial balls, installed in the fiducial posts, for the srQF, srQD and srQFA upper core segments were made on a horizontal boring mill. A fixture was made for mounting the assembled core half on the boring mill for machining the pole chamfers (Fig. 4). This fixture was provided with well defined features, which located reference surfaces (u/w plane direction and a front face surface for locating the longitudinal midpoint) on the assembled core. A set of datum surfaces was established for the mechanical fiducial measurements from this fixture. A cylinder with the same radius as the pole radius, in contact with two poles in the assembled half core, was used to define the u=0 and v=0 datums for the fiducial measurements. The w=0 origin was established at the longitudinal midplane of the upper half core.

Storage Ring Gradient Magnet (srB)

As of the writing of this paper, the first production srB has not yet been fiducialized. It is anticipated, however, that the mechanical fiducialization procedures will be performed on a large, newly purchased, CMM capable of handling the size and weight of an assembled gradient magnet. This CMM will be installed, tested and qualified during the summer of 1990. The u/w coordinate plane direction will be determined by the plane of the measuring device when the core is placed on the CMM bed on parallel rails in contact with the laminations of the core assembly. The longitudinal coordinate origin (w=0 plane) will be the plane longitudinally bisecting the magnet poles. The mechanical u=0 and v=0 origins will be established with a mechanical device, inserted in the magnet gap, carefully placed in contact with reference surfaces at well defined locations with respect to the mechanical origin of the coordinates of the pole contour.

Corrections for the Magnetic Center

The previous discussions described the method and procedures for measuring the coordinates of the tooling balls with respect to the mechanical coordinate system of the magnet. In perfectly symmetric and perfectly constructed magnets, the mechanical and magnetic centers of the magnets can be expected to coincide. Because the storage ring magnets need to be constructed in a manner to provide clearance for the synchrotron light ("C" shape geometry), there are well understood reasons for the displacement of the magnetic center from the mechanical center of the magnet. In addition, errors in magnet core fabrication or component assembly contribute to a further shift in the magnetic center These errors are of the same order of magnitude as the positioning tolerances of the magnet. Since the construction errors are non-systematic, the shift in the location of the magnetic center must be measured and a correction of the fiducial data must be made for each magnet.

For the booster ring magnets, having alignment tolerances larger than the storage ring, it was decided to use the fiducial ball coordinates referenced to the mechanical magnet center, without correction for magnetic center shift. Subsequent measurements of the booster-to-storage-ring (bts) quadrupoles,[4] which share virtually identical design with the booster quadrupoles, verified that the magnetic and mechanical centers of this magnet type differed by distances smaller than the alignment tolerances for the booster ring magnets (Fig. 5).

The multipole magnets (quadrupoles and sextupoles) are magnetically measured using a slowly rotating line integral coil, integrating the electrical output voltage and performing a Fourier analysis of the integrated signal. It is important to note that the housings for the line integral coils are fabricated in a manner such that they register on the same surfaces of the core segment as the cylinders used to define the mechanical u=0 and v=0 datums. Thus, a coil rotational axis coincides with the mechanical axis established during the mechanical fiducialization process. The output data from this process are multipole field errors, evaluated at a fixed (arbitrary) radius and normalized by the fundamental field evaluated at the same radius.

Storage Ring Quadrupole (srQF, srQD and srQFA)

It can be shown that the displacement of the center of the measuring coil from the magnetic center of the quadrupole can be characterized by. the following equations:[5]

$$\Delta x = \frac{a_1}{|B_2|} \cdot r_0 \qquad \text{and} \qquad \Delta y = \frac{b_1}{|B_2|} \cdot r_0$$

where a_1 and b_1 are the in-phase and skew components of the dipole field, [B_2] is the magnitude of the quadrupole field and r_0 is the normalizing radius for the measurement. A_x and A_y are measured in the same distance units as r_0. The storage ring quadrupole mechanical fiducial ball data will be corrected for the offsets calculated using the magnetic measurement data.

Mechanical measurements of the coils in their precision housings were made. These measurements indicate that the quadrupole rotating coils axis lies within an error circle of radius 20 µm of the center of the mechanical indexing points of the core. The sextupole rotating coil has an error radius of 15 µm.

The sensitivity of this center measurement was demonstrated by intentionally shimming the search coil with respect to a reference position (Fig. 6). The results of this test are shown in Fig. 7 for the quadrupole.[5]

Storage Ring Sextupole (srSF and srSD)

It can be shown that the displacement of the center of the measuring coil from the magnetic center of the sextupole can be characterized as follows:[6]

$$\Delta x = \frac{a_2}{2\,|B_3|} \cdot r_0 \qquad \text{and} \qquad \Delta y = \frac{b_2}{2\,|B_3|} \cdot r_0$$

where a_2 and b_2 are the in-phase and skew components of the quadrupole field, $|B_3|$ is the magnitude of the sextupole field. (Because of the quadratic nature of the sextupole offset errors, determination of the offsets using the dipole errors would not result in a unique solution. Two offset values would be computed since the quadratic equation has two linear solutions.) The sensitivity of this center measurement was demonstrated by intentionally shimming the search coil with respect to a reference position (Fig. 8). The results of this test are shown in Fig. 9. The correspondence of the magnetic center data with the apparent physical location of the magnetic center using the shimming information is not as clear as it is with the quadrupole offset graph. However, the “family resemblance” of the offset plots indicates that the magnetic measurement technique for correcting the fiducial data is sensitive and reliable and will yield a better characterization of the magnetic center than the mechanical center. The storage ring sextupole mechanical fiducial ball data will be corrected for the offsets calculated using the magnetic measurement data.

Storage Ring Gradient Magnet (srB)

The magnet-to-magnet reproducibility tolerance for the storage ring gradient magnet requires that the integrated field for each magnet does not vary from the mean value by more than 1 part in 1000. At the writing of this paper, eighteen of the required thirty-six cores have been assembled. The mechanical length measurements of the cores indicate that the reproducibility requirements will be satisfied. However, since the magnet is designed with a constant gradient, an opportunity exists for compensating for any deviation greater than this tolerance by aligning the magnets with a slight offset from the locations determined by their mechanical features. Magnetic measurements will include precision Hall probe longitudinal maps of the production magnets with the axis of these maps precisely located by means of a laser/target setup, capable of measuring offsets of the order of 5 μm. The laser line of sight will be set up at the same location as the datum device used to provide a u=0 origin for the mechanical fiducialization procedures. The Hall probe data will be integrated and compared with the field integral data of other magnets of this type. Any magnet whose field integral differs by an amount which exceeds the reproducibility tolerance will have its fiducial data adjusted to provide an offset alignment such that the magnet gradient will compensate for the deviation in the field integral.

Fiducialization of Booster Girders

For each of the four booster ring bend sections, there are three girders on which the magnets are mounted. Each of these girders carries six fiducial posts, identical to the ones used on magnets. Furthermore, two precision bores are drilled into the top surface of every girder, one at the intersection of its longitudinal symmetry line with the vertical projection of the ideal beam trajectory and the other one near its downstream end (Fig. 10). The axis of the first hole defines the origin of the girder coordinate system, and the connecting line between the centers of the two holes defines the longitudinal (w axis) direction of a girder. The roll angle of a girder during a fiducialization procedure is determined by the position of the outer, central fiducial.

Because of the actual surface height variations of the girders, however, these definitions are not yet complete. The vertical location of the girder coordinate system origin is defined to be on the adjustment plane determined by the centers of all six girder fiducials, and this plane also determines the vertical directions of the two transverse coordinate axes (u and w). The calculation of the numerical coefficients of these adjustment planes is performed either by the survey software package ECDS[7] or by the software application 'Mathematical.[8] Both methods have led to identical plane coefficients. All principal features of the girders are mathematically projected into the adjustment planes, to completely define the girder coordinate systems. A nominal girder surface elevation is then defined to be below the adjustment plane by one ideal fiducial post height.

The fiducialization procedure is performed by observing the centers of the six fiducials and of the two reference bores by theodolites and calculating their positions using ECDS. To obtain an absolute scaling factor, a calibrated scale bar is included in the observations. A detailed description of the surveying techniques used for ALS is given in Ref. 2. Multiple repetition of the entire fiducializing procedure for two girders demonstrated that the expected accuracy of fiducial coordinates obtained from a single procedure amounts to 0.12 mm RMS longitudinally and 0.02 mm RMS transversely and vertically.

Acknowledgements

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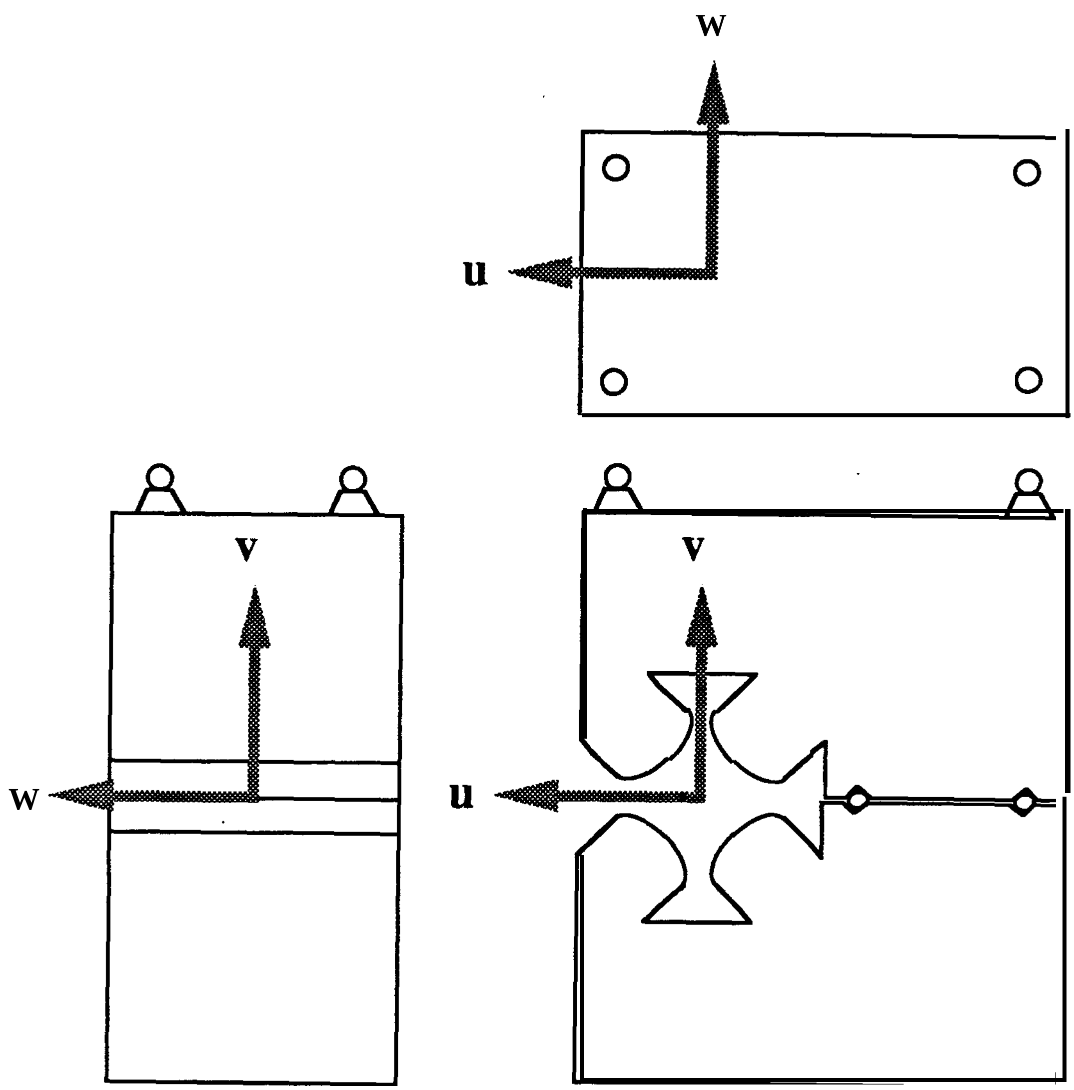

Fig. 1. Magnet Coordinate Axes

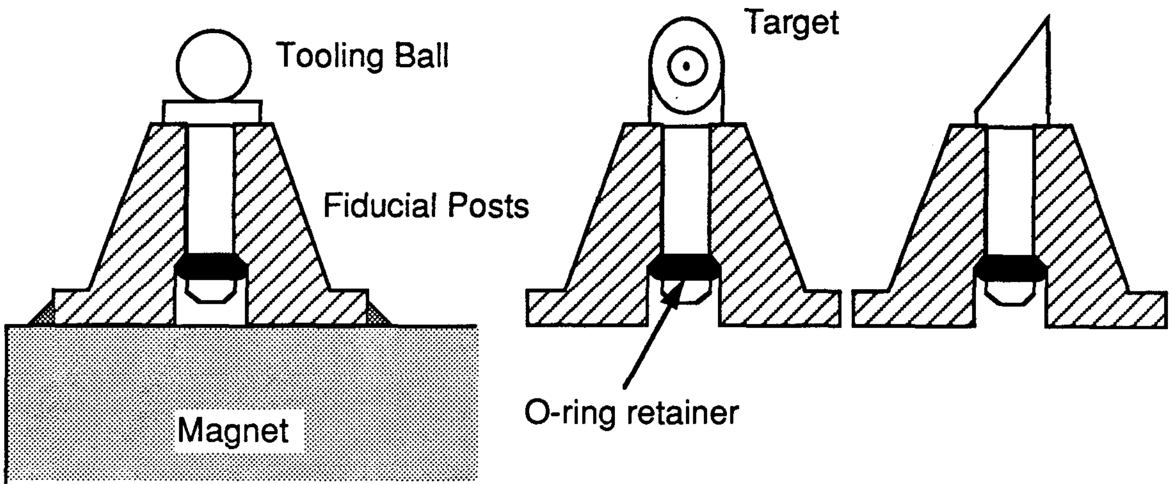

Fig. 2. Fiducial Post, Tooling Ball and Target

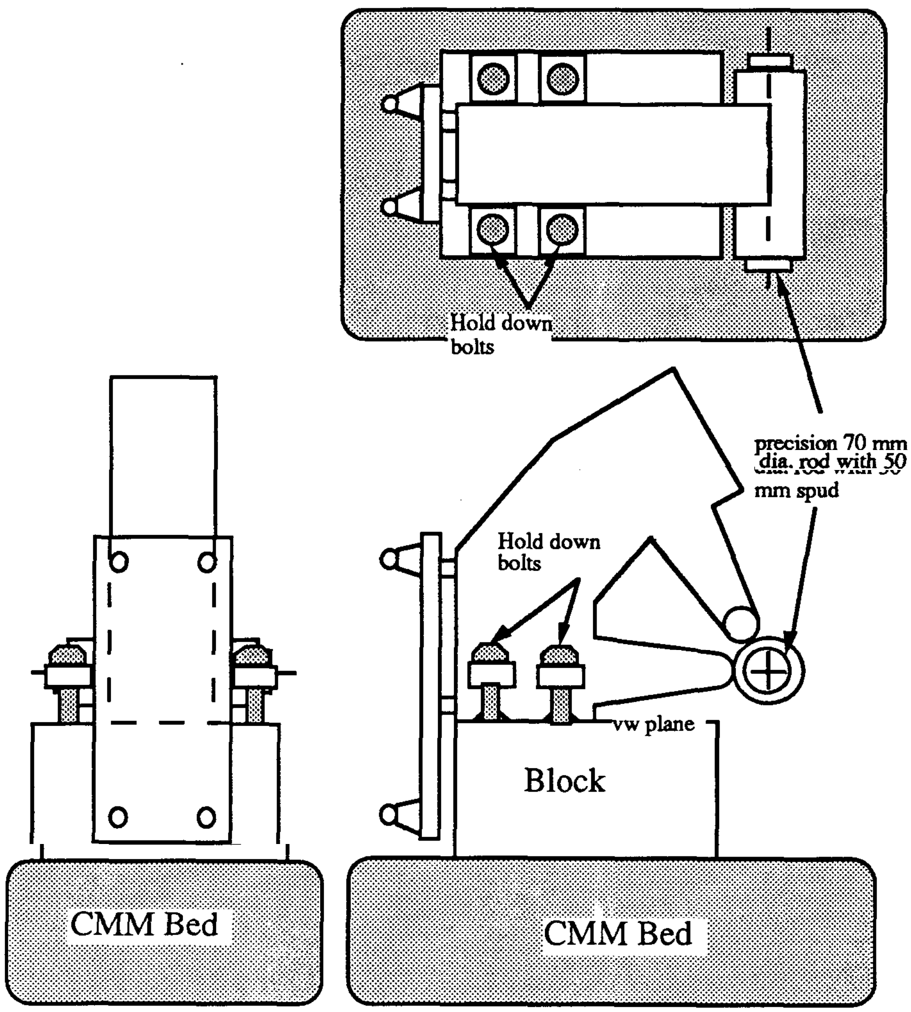

Fig. 3. Mechanical Fiducialization Setup
for the Storage Ring Sextupole Core Segment

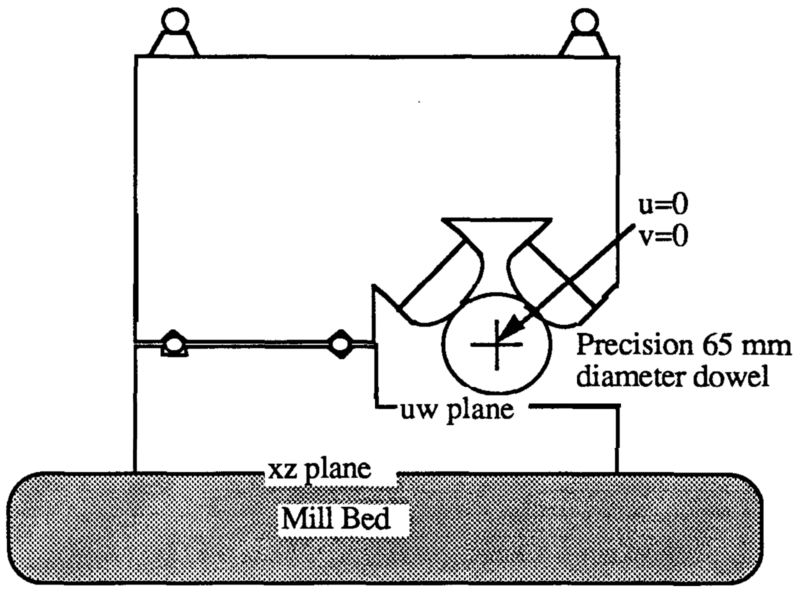

Fig. 4. Mechanical Fiducialization Setup
for the Storage Ring Quadrupole Core Segment

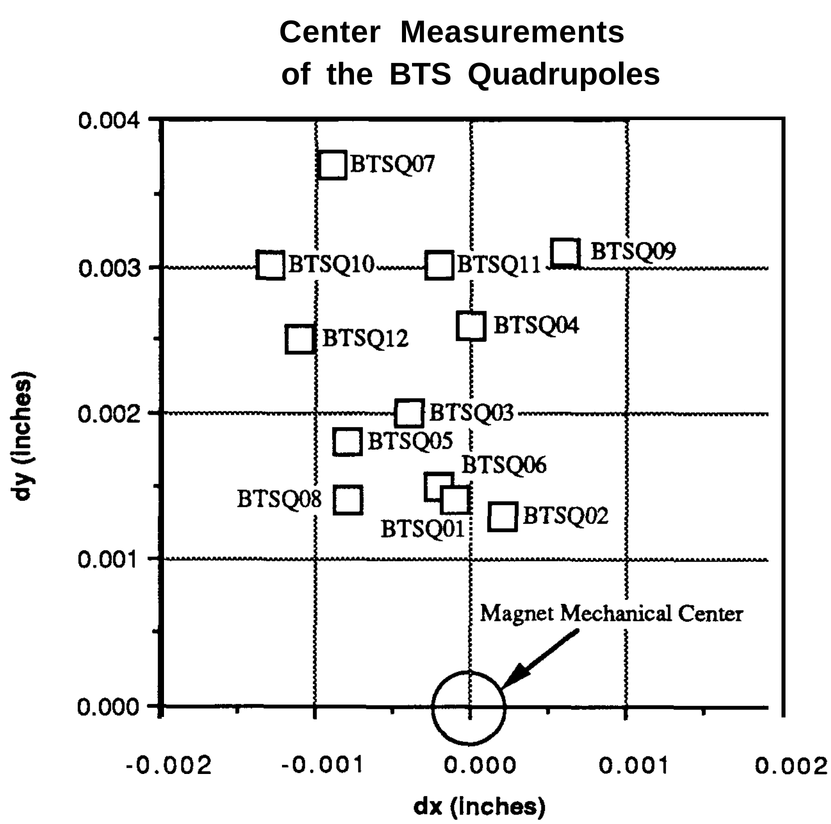

Fig. 5. Distribution of Deviation of Magnetic Center from the Mechanical Center for the Booster to Storage Ring Transfer Line Quadrupoles

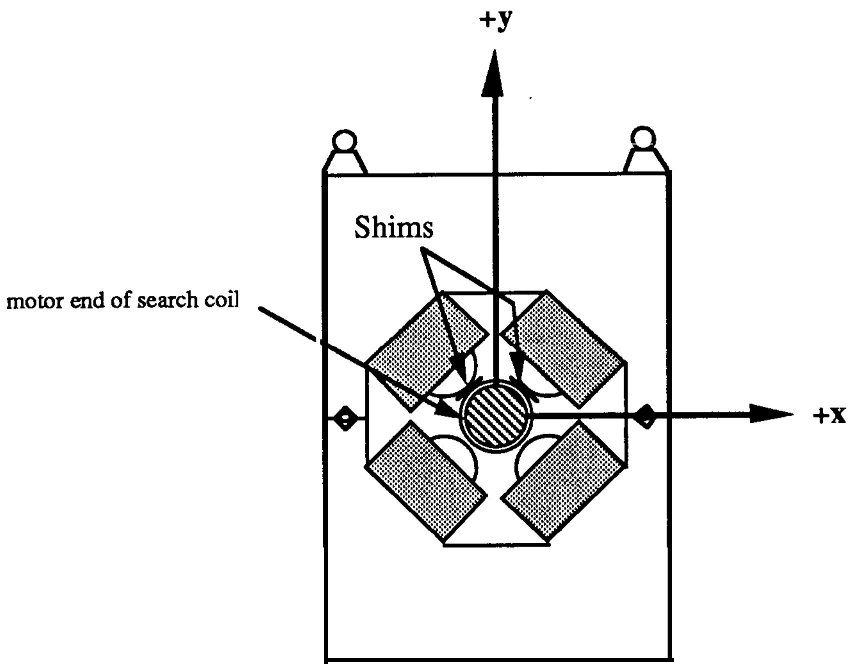

Fig. 6. Mechanical Shimming of the Booster to Storage Ring Quadrupole

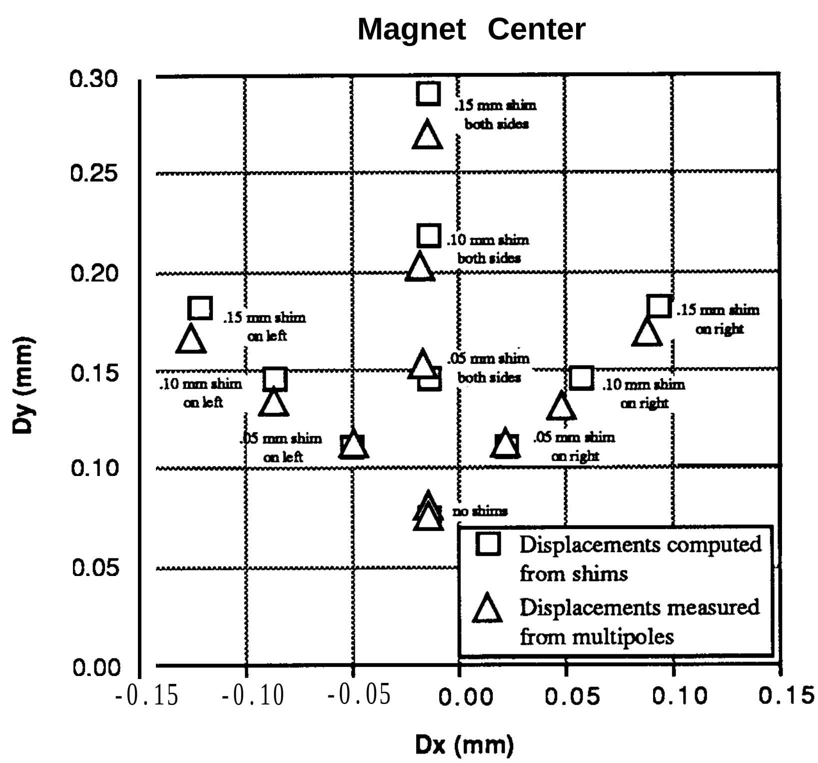

Fig. 7. Displacement of the Apparent Magnetic Center by Shimming the Search Coil for the Booster to Storage Ring Transfer Line Quadrupoles

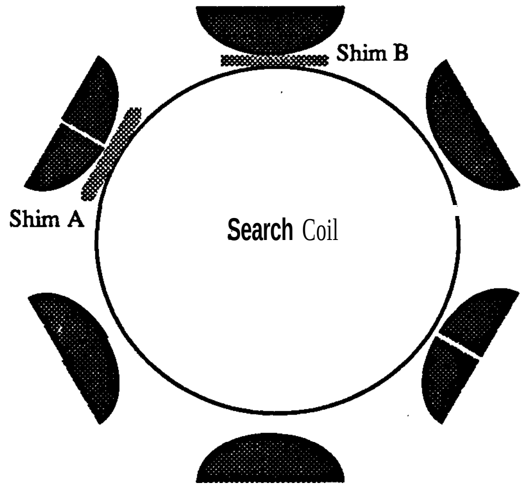

Fig. 8. Mechanical Shimming of the Storage Ring Sextupole

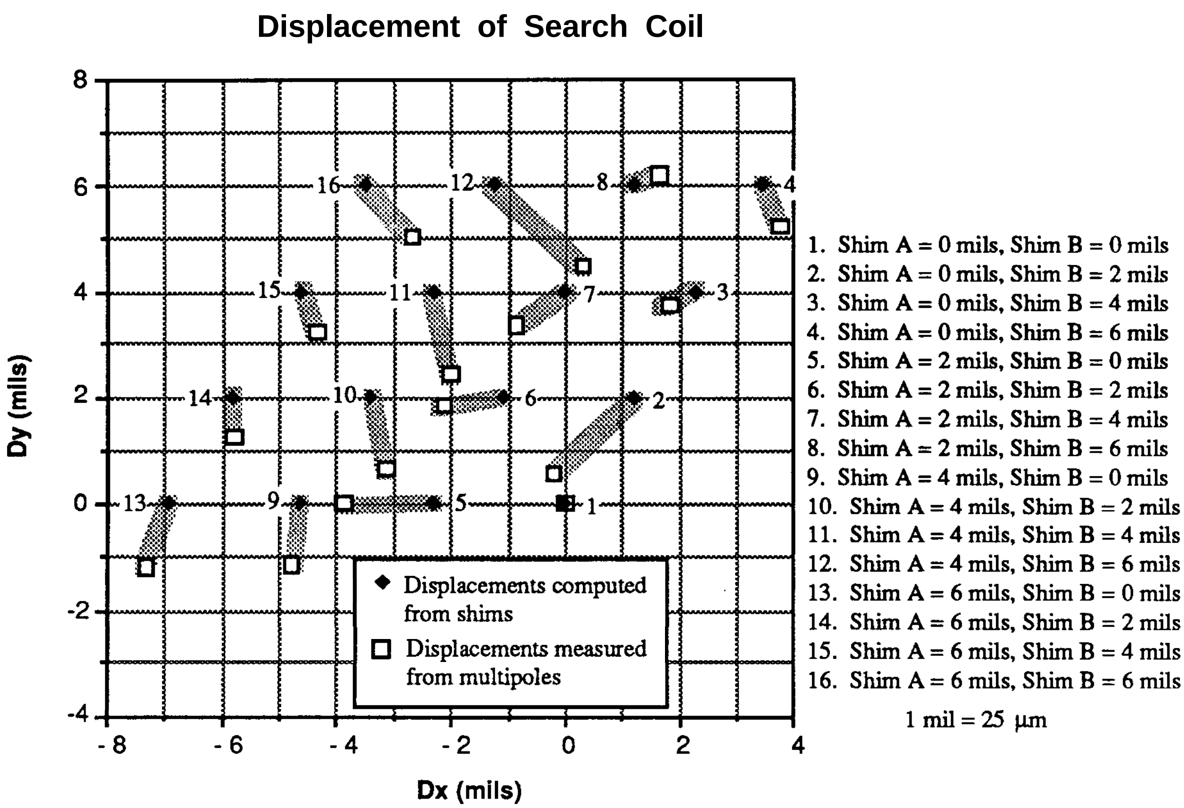

Fig. 9. Displacement of the Apparent Magnetic Center by Shimming the Search Coil for the Storage Ring Sextupole

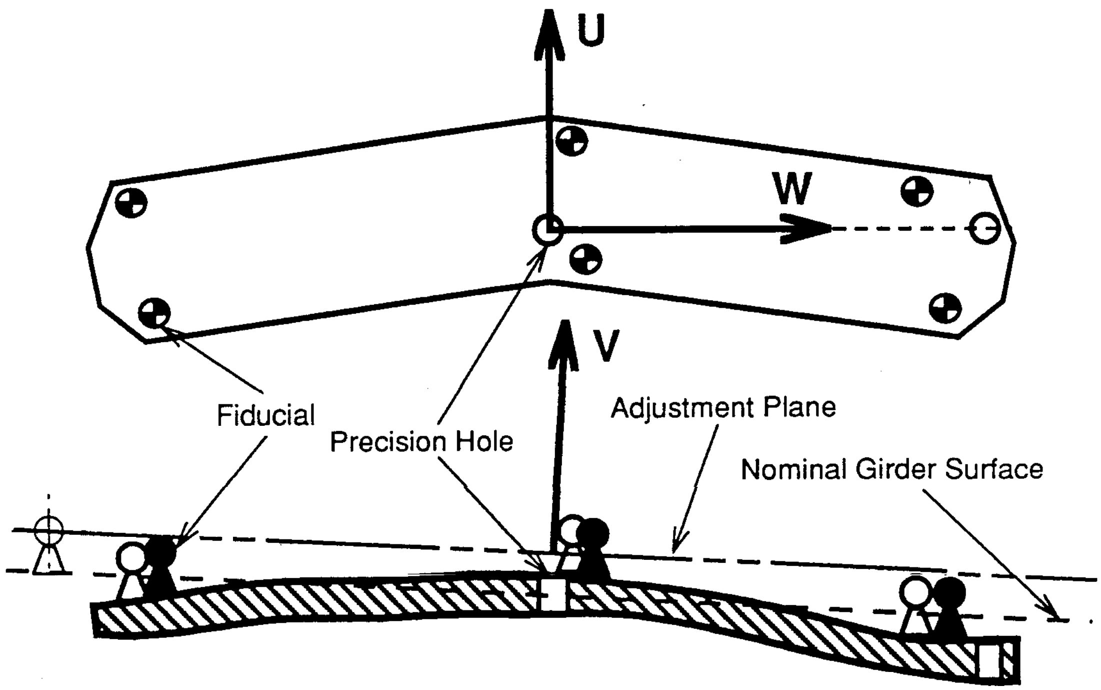

Fig. 10. ALS booster girder in plan view (top) and elevation view (bottom). The surface height variations are strongly exaggerated. In the girder symmetry plane, the electron beam moves parallel to the W direction.