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R. Keller

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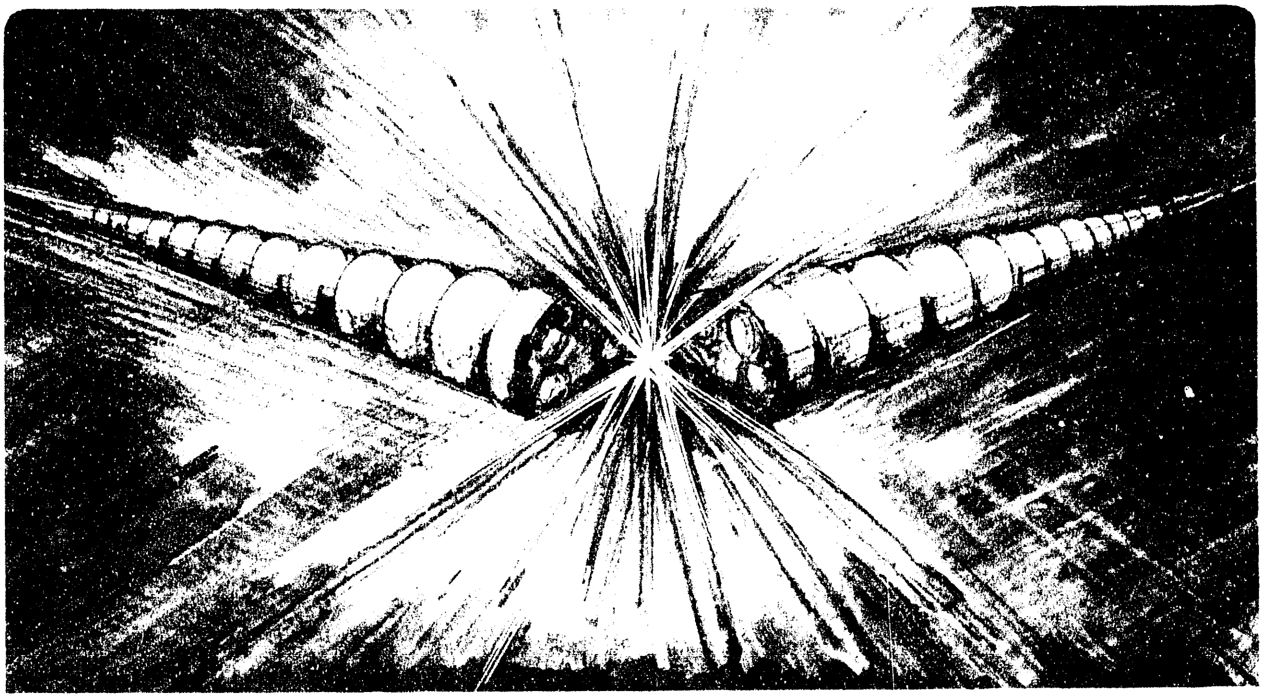

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RODERICH KELLER

ACCELERATOR & FUSION RESEARCH DIVISION
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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Roderich Keller
Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, U.S.A.

1. INTRODUCTION

The Advanced Light Source (ALS) electron storage ring, now being commissioned at Lawrence Berkeley Laboratory, is the main accelerator of a third-generation synchrotron radiation source designed to produce extremely bright photon beams in the UVand soft X-ray regions [1]. The 1-1.9 GeV ring consists of 12 superperiods with 196.8 m total circumference and has particularly tight positioning tolerances for lattice magnets and other components to assure the required characteristics.

The general survey and alignment concept for the ALS [2] is based on a network of fixed, three-dimensional monuments installed in the building floor, to which all accelerator component positions are referred. The survey of these monuments is performed separately for horizontal and vertical coordinates, following the scheme imposed by the code PC-GEONET [3] that is used for monument data analysis [4]. For most of the accelerator objects the tasks of data acquisition, bundling, and transformations from observation-station into object coordinate-systems are being handled by the commercial software package ECDS® rather than by PC-GEONET. This choice had to be made because no instrument stands are presently available at LBL that can be placed exactly over monuments and are high enough to permit observing the fiducials of installed magnets from above. Theodolites only are used with ECDS as observation instruments, and absolute scaling has to be provided by observing some object of precisely known length.

To create ideal data and compute alignment values for all accelerator components, spreadsheets were developed by the author using the application EXCEL® for Macintosh® computers. Choice of a spreadsheet method rather than conventional programming techniques proved very convenient when in the course of this work the sheets had to be created and progressively modified under severe time pressure to include new effects and help redefine the observation procedures. With spreadsheets, varying input data formats coming from the survey crew could be easily accommodated, and adding numerous consistency checks as well as generating additional ideal data for special alignment tasks was possible with comparatively little effort. Dedicated spreadsheets were created for each of the 12 curved sectors of the storage ring.

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In this paper, the main features of the spreadsheets are presented, and the alignment results for lattice and corrector magnets are listed and discussed.

2. SCOPE AND TOLERANCES

Storage ring objects designated for precision alignment include: a), lattice magnets (36 bend magnets, 72 quadrupoles, and 48 sextupoles); b), 46 corrector magnets; c), special magnets (2 septa and 4 bump magnets); d) 12 storage ring vacuum chambers, represented by 96 beam position monitors (BPM), 8 per chamber; e), 2 rf cavities; and f), special objects (photon beam-line components and gate valves). The arrangement of most of these objects is illustrated in Fig. 1, and a list of required local tolerances for objects discussed in this paper is given in Table 1. These entries are understood as 1-σ values of each error distribution, with a 2-σ cut-off. No strict global tolerance value is established.

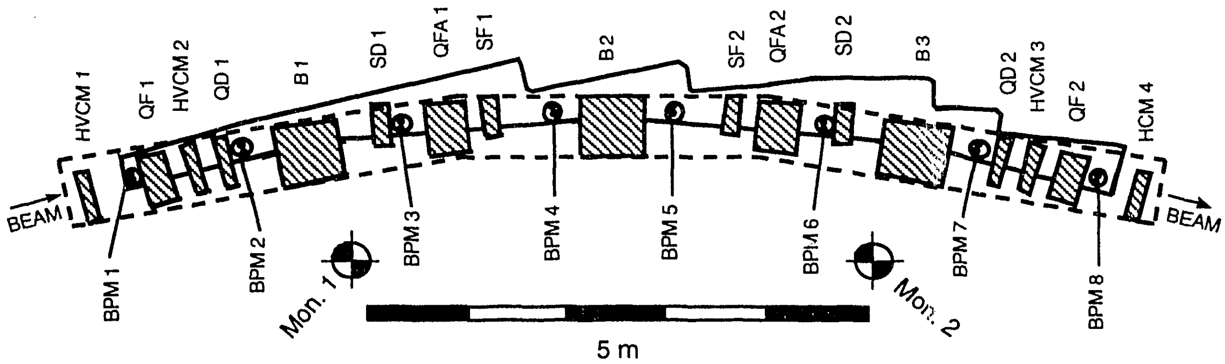


Figure 1. Storage ring magnet arrangement in one curved section, with outlines of vacuum chamber (solid line) and girder (broken line). For designations of magnets and other objects, see Table 1. Four monuments, Mon., are used as survey references; two of them, near the adjacent straight section centers, are not shown in this figure.

Every magnet carries four fiducial posts that are welded to its upper side without attempting to achieve any precise positioning; the positions were determined by a coordinate measurement machine. The magnet outlines in Fig. 1 represent the locations of these four fiducial posts, in the corners of every rectangle, rather than the true outlines of the magnet yokes or pole pieces. Different exchangeable targets are used on these posts, either optical targets with engraved circle and center point for surveying or tooling balls, for alignment in combination with dial indicators or for optical tooling methods. The BPM flanges can be equipped with two targets, each, but one only is routinely used for survey and alignment tasks. Originally, BPM positions had been evaluated using ECDS, but after installation of magnets on the girders the BPM fiducials could no longer be observed from theodolite stations. Therefore, the curved vacuum chambers were fine-aligned using optical tooling methods [5].

Table 1

Local Alignment Tolerances

Object	Δw [mm]	Δu [mm]	Δv [mm]	Δu' [mrad]	Δv' [mrad]	Δw' [mrad]
B	0.15	0.15	0.15	./.	./.	0.25
QD	0.3	0.15	0.15	./.	./.	0.5
QF	0.3	0.15	0.15	./.	./.	0.5
QFA	0.3	0.15	0.15	./.	./.	0.5
SF	0.5	0.15	0.15	./.	./.	./.
SD	0.5	0.15	0.15	./.	./.	./.
HVC	1.0	1.0	1.0	./.	./.	2.0
BPM	0.15	0.15	0.15	./.	./.	./.

The entries in Table 1 stand for: B, bend magnet. QD, defocusing quadrupole. QF and QFA, focusing quadrupoles. SF, focusing sextupole. SD, defocusing sextupole. HVC, horizontal and vertical corrector magnet. BPM, beam-position monitor. Tolerances are described in local, beam-following coordinates: w, in beam direction; u, radially away from the ring center; v, vertically up. u', pitch; v', yaw; w', roll. ./. indicates that these values are predetermined by other values in this table.

3. INSTALLATION AND ALIGNMENT

Magnets and vacuum chambers are mounted on girders spanning one of the twelve curved storage-ring sectors each, see Figure 1. In the first phase of installation, the vacuum chambers are precisely aligned to their girders, represented by 12 girder fiducials. Then the magnets are installed and fine-aligned to the girders as well. As a last step, girders and their objects are aligned to the global 'ALS Coordinate System' represented by the four floor monuments in the immediate neighborhood of every girder. This scheme led to the creation of two families of spreadsheets in which object-alignment data were computed, the so-called 'girder' and 'monument' sheets.

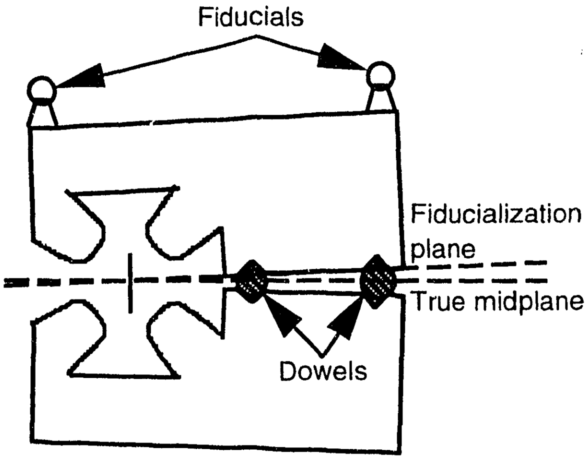
The concept of separation between local alignment of objects (magnets or chambers) to girder fiducials and final global alignment of girders to monuments is well suited in principle to minimize the entire effort, but in reality it failed because the girders bent too much under the weight of the installed magnets, and thus the original girder fiducialization was lost. Therefore, some magnets had to be fine-aligned using survey data related to the global monument sytem, and the final alignment of the vacuum chambers was performed using optical tooling methods because most BPM fiducials, representing the chambers, are hidden between the magnets.

All alignment values are ultimately expressed in local, beam-following coordinates along the main object axes to facilitate the orientation of dial indicators with which the alignment is controlled on every fiducial. Even the alignment to monuments, executed by moving girders only, is monitored on selected magnet fiducials, to achieve final alignment of lattice magnets to the global ALS coordinate system in the most direct manner.

4. CREATION OF IDEAL DATA

Ideal data for all objects included in the survey and alignment effort are created in yet another line of spreadsheets, based on mechanical fiducialization data [6] and magnetic measurements [7]. Special effects are accounted for, such as the measured magnetic-to-mechanical axis offsets for quadrupoles and sextupoles, and roll angles introduced by shimming the two halves of every quadrupole, as seen in the schematic diagram below.

The roll angle between the true midplane and the original fiducialization plane of a quadrupole magnet is created by shimming it with two dowels of different widths between the two core halves. The shimming is needed to eliminate the magnetic sextupole field component caused by the asymmetric yoke design.



These data, together with an accelerator lattice file [8] and the information on the chosen lattice position of any given magnet in the entire ring are being used to convert all fiducial data from local magnet systems into a generic girder system whose origin horizontally coincides with the intersection of the tangents to the ideal beam trajectory on both sides of the central bend magnet. The transformation into the global ALS system is done inside the 'monument sheets,' individually for every storage ring sector.

5. GIRDER SHEET

The Girder Sheet is the first of the two spreadsheet varieties in which ideal and observed magnet fiducial positions are compared and then adjusted correction values are computed. As a first step, the ideal magnet fiducial data are modified to account for the measured offset of the vacuum chamber center against the ideal girder system. The chambers cannot be moved in this area because they are anchored on a pinned stanchion. After calculating the ideal-to-observed position differences in all three directions of this modified girder system, the longitudinal difference values are compensated for thermal expansion of the girder at the time of surveying. Observed lateral girder deformations, caused by their inner support structures, ultimately made it necessary to maintain the entire storage ring tunnel at the design temperature (23.9 ±1°C) during surveys, but the longitudinal compensation algorithm is kept in the girder sheets as a safeguard against larger actual temperature excursions.

Two kinds of consistency checks are permanently included in the Girder Sheets, a comparison of the distances between all fiducials of one magnet from both optical and mechanical measurements, and a comparison of all distances between the four observed monuments with the same values derived from the latest dedicated monument survey. These latter ("ideal") monument distances are included as constants in the ECDS data file to provide absolute scaling.

To facilitate an easy set-up of the dial indicators the derived magnet correction values are transformed from the common girder coordinate system into individual magnet systems. Because of the redundancy of information provided by 12 coordinate values some adjustments are made before the correction values are finalized. The precision of the original installation, compared to magnet dimensions, allows one to compute the adjusted corrections sequentially, rather than as a true rigid-body movement. For every magnet, the average shifts along its own major axes are calculated first, and the remaining correction values are used to evaluate average yaw, pitch, and roll angles which are then translated back into fiducial shifts along the magnet axes, to be superimposed on the average shifts.

6. MONUMENT SHEET

The Monument Sheet computes the final alignment values for all magnets, to be executed by moving entire girders only. This implies that all magnet correction values are averaged to yield global girder corrections, i.e. average shifts in three directions and three angular rotations. These global corrections, however, are then expressed as shift values for one fiducial, each, on the two focusing quadrupoles at the end of every girder (horizontal and vertical directions) and on the central bend magnet in the girder center (vertical direction only), see Fig. 2. Because this set of data is still slightly redundant the longitudinal corrections dw are averaged between the two quadrupole fiducials.

Monument Sheets include the same consistency checks as Girder Sheets, but their input and ideal data are expressed in the global ALS coordinate system. One given set of observation data can be easily transformed by ECDS into both ALS and individual girder systems.

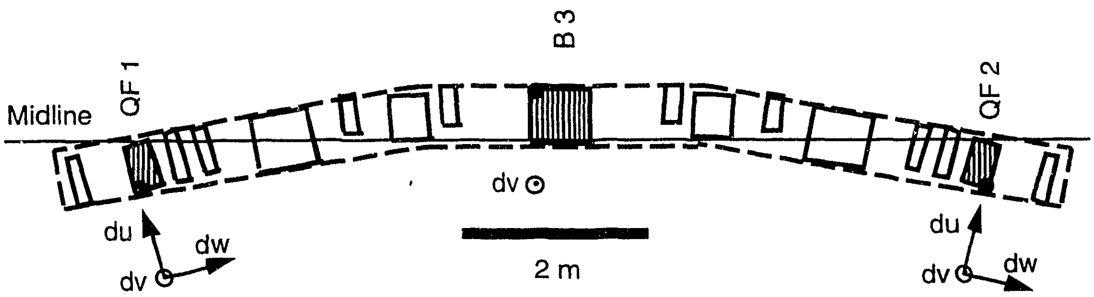


Figure 2. Global girder alignment, monitored on three magnet fiducials (full black circles on hatched magnet outlines) in local magnet coordinate systems {du, dv, dw}. The girder midline is defined by the average of the transverse coordinates of all magnet fiducials.

After the initial calculation of ideal-to-observed fiducial position differences in the ALS system, these values are transformed into the corresponding girder system, and the temperature compensation algorithm is applied. At this point there is the option to merge individual magnet corrections, resulting from executing the values obtained from the Girder Sheet, into the Monument Sheet, reducing its remaining corrections accordingly. The average shifts for all magnets are calculated next, and from the remaining correction values the three angular corrections are determined. For pitch and yaw, only magnets at the ends of the girders, including the outer bend magnets, are taken into account, and for roll, only those fiducials are taken that are more than 250 mm away from the girder midline, see Fig. 2. The evaluated angles are then used for a second-order correction, assuring that the average shift for all fiducials resulting from the angular corrections is exactly zero. In addition, the differences between all individual corrections and the effects of the computed global corrections on every magnet fiducial are displayed for visual inspection. All fiducial corrections resulting from the global girder corrections are transformed into local magnet coordinate systems, but the reference fiducial corrections actually to be used for monitoring the girder alignment are displayed together again and printed as a work sheet for the alignment technicians' use.

7. RESULTS

Ideally, 3 surveys and 2 alignments are the minimum number, but due to girder deformation under temperature changes and mechanical load, changes of the scaling reference, ground motion, and bakeout of two vacuum chambers, it took 7.7 surveys on the average to reach good alignment for all magnets. Two girders actually needed three surveys only, each. The final lattice magnet alignment was much better than specified, with remaining errors being 2.5 times smaller than the established tolerances. This result fully qualifies the validity of the used procedure, where the tasks of local and global alignments were separated. As an illustration, two sets of data are presented in Tables 2–3. They represent standard deviations of the remaining position errors for all lattice magnets in absolute, Table 2, and after subtracting a linear fitting line separately for every girder in the transverse coordinates, and the average error in the longitudinal coordinate, Table 3. Roll errors are given as absolute standard deviations in Table 2, and as averages of absolute errors in Table 3.

Table 2

Final Absolute Alignment Errors

	dw [mm]	du [mm]	dv [mm]	Roll [mrad]
QF	0.17	0.11	0.20	0.07
QD	0.15	0.08	0.20	0.08
QFA	0.14	0.08	0.19	0.08
B	0.14	0.09	0.19	0.07

Table 3

Final Local Alignment Errors

	dw [mm]	du [mm]	dv [mm]	Roll [mrad]
QF	0.13	0.03	0.04	-0.06
QD	0.10	0.04	0.02	-0.05
QFA	0.05	0.03	0.02	-0.07
B	0.08	0.03	0.02	-0.04

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[3] H. Friedsam, R. Pushor, and R. Ruland, SLAC-PUB-4142, (1986).

[4] Data evaluation using PC-GEONET was performed by H. Friedsam and M. Gaydosh as part of a collaboration agreement between LBL and SLAC.

[5] All alignment work, including optical tooling, was performed by ALS staff led by B. Baldock and R. De Marco.

[6] Magnet fiducialization was performed by members of the ALS Mechanical Engineering group, guided by T. Lauritzen, J. Tanabe, and T. Henderson.

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