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SLC ARC TRANSPORT SYSTEM—AG–MAGNET MEASUREMENT AND PERFORMANCE*

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ABSTRACT

This paper describes the design, construction, and operation of devices used to rapidly measure the mechanical and magnetic properties of some 950 Alternate gradient magnets[1] used in the arc system of the Stanford Linear Collider. The problems of dealing with the measurement of the transverse dimensions to within minute (0.0001 in) resolution of objects that are 8 ft long are discussed. Early results from the production runs of these magnets are presented.

INTRODUCTION

The trend toward higher energy machines with smaller emittances has had concomitant effects on magnet design. Magnets are becoming very much longer and their apertures are getting smaller. This presents challenges in mechanical and magnetic measurement techniques. The SLC Arc magnets become a case in point.

For an "iron dominated" magnet (not in saturation and using well shuffled steel) there should exist well defined correlations between its geometric dimensions and magnetic performance. We will not be so bold as to suggest that this correlation can be calculated in an absolute way to the required accuracy, but experience with an ensemble of over 400 PEP dipoles[2] and quads indicated that one could have predicated their field imperfections from their dimensional imperfections with sufficient accuracy. Since mechanical measurements can, in general, be made quickly, we have decided to measure all cores mechanically, perform enough magnetic measurements to establish a correlation, thereby providing the necessary statistical basis and sample then the remaining distribution magnetically at a 10% level.

TOLERANCES OF THE DESIGN PARAMETERS

The major part of the Arc transport system consists of Achromats which are designed to cancel chromatic and second order geometric aberrations. To preserve these properties magnetic field errors and misalignments have to be controlled to an unprecedented degree. Every focusing magnet can be moved horizontally and every defocusing magnet can be moved vertically for correcting horizontal and vertical centroid errors.

With the design and the configuration of the AG magnet as given in Ref. 1, simulations have shown that field errors should be no greater than those created by misalignments of ~ 100 μm rms in each transverse dimension. Fabrication tolerances which in turn affect the ability of determining the location of the equilibrium orbit, therefore follows with comparable magnitude. The resultant tolerances on the random field and dimension errors are summarized in Table I.

TABLE I. Tolerances of Random Imperfections

A. Field Imperfections					
1.	Dipole field	$\Delta B/B$	~	0.012	
2.	Gradient field	$\Delta G/G$	~	0.003	
3.	Sextupole field	$\Delta S/S$	~	0.05	
B. Dimension Imperfections					
1.	Length	ΔL	~	0.050	in
2.	Gap	Δg	~	0.001	in
3.	Sagitta	Δs	~	0.004	in
4.	Height	ΔH	~	0.004	in
5.	Roll	ΔR	~	1.000	mrad

Because the magnet is curved to conform with the particle trajectory, the definition of the length of the magnet is along the curved path. The "gap" is defined to be the average distance of the closest separation of the upper and lower poles, although the usual definition is at the location of the orbit. The "sagittal" value is defined to be the central distance from the core (a straight line linking the iron entrance and the exit of the magnet) to the circular path. For our magnet it is 0.108 in.

"Height" is defined to be the vertical distance of the upper pole with respect to arbitrary reference level. It is a measure of the vertical straightness of the core. Finally the roll is the angle of rotation of the lamination with respect to the beam axis. Twist is the variation of the roll as a function of length.

Relationships between dimension errors and field effects will be discussed in Sect. 5.

THE MECHANICAL MEASUREMENTS

The SLC Automatic Magnet Measuring Instrument (SAMMI) was designed to determine the core's gap, vertical height, sagitta, and roll as a function of length. Sensors are mounted on a carriage which travels back and forth on a 12 ft long accurate stone slab which serves as the reference bed[3]. A photograph of the SAMMI device is given in Fig. 1.

For gap and height, a "Lasermike"[4] whose photo-diode was modified to fit inside the magnet gap gauges the shadows cast

Fig. 1. The SLC Auto Magnet Measuring Instrument (SAMMI).

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by the upper and lower polepieces by measuring the occultation time of a laser light signal in relationship to the rotation of its spinning mirror. The resolution is better than 0.0001 in and averages are taken at the rate of 100/sec thereby monitoring, in situ, the stack structure of the laminations and even the variations caused by "die break."

For sagitta and roll, two "eddy current impedance"[5] proximity sensors are used to measure the horizontal distance of the upper and lower pole faces from the reference line. The average of these distances yields the sagitta offset of the curved gap, the difference yields the roll and the twist. The dynamic range of the sensor head chosen is only .25 in but its resolution is better than 0.0001 in. It averages its reading over about ten laminations thereby overcoming the problem of "bur" variation. To guarantee uniform eddy current readings a thin aluminized sticky tape is placed on the surface of the magnet face.

After a magnet is mounted, (there are two stations, one for each magnet type) it takes only a few minutes to make 200 measurements along the length of a core. The data are automatically acquired by a CAMAC interfaced IBM-PC-XT microcomputer. On-line graphic displays are provided as well as file storage in the laboratory's main computer network for archiving, retrieval, and further analysis.

For each parameter measured the average and the RMS deviation are immediately generated. During the development of magnet construction techniques SAMMI were used as a guide for procedural improvement. In the present production run it is used as the primary tool of our quality assurance program. An example of a summary of one run (magnet AGD081D) is reproduced in Table II.

TABLE II. SAMMI Run for Magnet AGD081D

	Design	Average	Deviation
Length	97.612 in	97.646 in	0.034 in
Sagitta	0.108 in	0.109 in	0.001 in
Gap	0.3172 in	0.3189 in	0.0017 in
Height	0.153 in	0.155 in	0.002 in
Roll	0.0 mrad	0.562 mrad	0.562 mrad

A comparison of this result with the criteria listed in Table I, shows that most of the parameters are acceptable, gap excluded. We will show in Sect. 5 that the gap is also acceptable as long as the gaps of all the magnets open up in a systematic way.

THE MAGNETIC MEASUREMENTS

The aperture of this magnet is too small as well as being curved for a conventional measurement. To measure the integrated $B \cdot dL$ we have constructed 2.5 m long search coils by winding ten turns of #38 wire on flexible fiberglass forms which were ground to a thickness of 1.0 mm. These coils were in turn fastened to flat rigid frames, (one for the focus the other for defocus type) whose curvature had been machined to match the bending radius of the particle orbit. This assembly can be laterally plunged into the gap from a location outside the magnet where its fringe field is small and measurable by conventional means.

The motion is performed by refurbished bubble chamber track measuring stages which have a resolution of 2 μm. The setup can be seen in Fig. 2. To check the performance of each stage, the horizontal position of the coil is measured at both ends by SONY digital transducers[6] of 1 μm resolution. The absolute position of the coil relative to the core is set by means of an optical tooling microscope to within ~ 25 μm. The total assembly has to be quite massive to resist the unbalanced forces of the bus bars and floor vibrations. Interesting thermal and mechanical problems had to be solved before the data became reliable and reproducible.

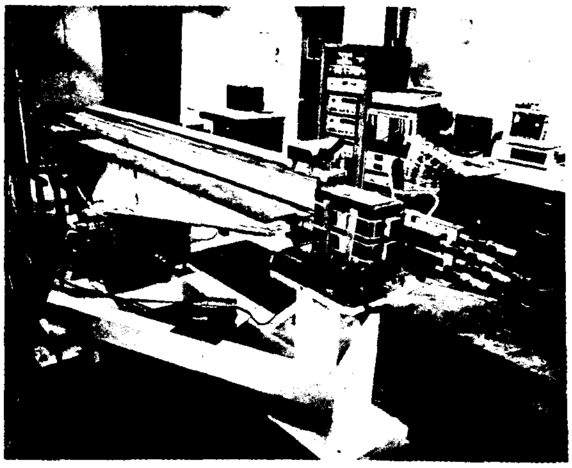

Fig. 2. The magnetic measurement apparatus.

Flux changes as a function of x are digitized by an integrating voltmeter and analyzed to yield the length integrated dipole, quadrupole, sextupole and higher, if any, field components. The whole system, including the 6 V, 6000 A power supply is controlled by a CAMAC interfaced IBM-PC-XT which is also served as an online data manager. The files are archived in the laboratory's main computer.

Before a magnet is measured, it has to be "initiated" and "standardized" to assure its "magnetic history." Following this procedure guarantees reproducibility within one setup of 0.1%.

Shown in Fig. 3 are the results of one typical measurement where various curves correspond to different excitations. The curves are then fitted by a third order polynomial to find the dipole, quadrupole, and sextupole components of the magnet and the result are shown in Fig. 4. It can be seen that the fields are linear up to 4000 A, ~ 50 GeV operation, then start to have some saturation effect. Fortunately the saturation effects are similar for all three components.

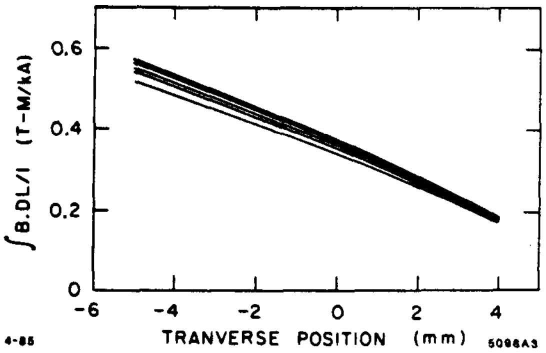

Fig. 3. Integrated strength per unit current ($T\text{-}M/kA$) vs. X.

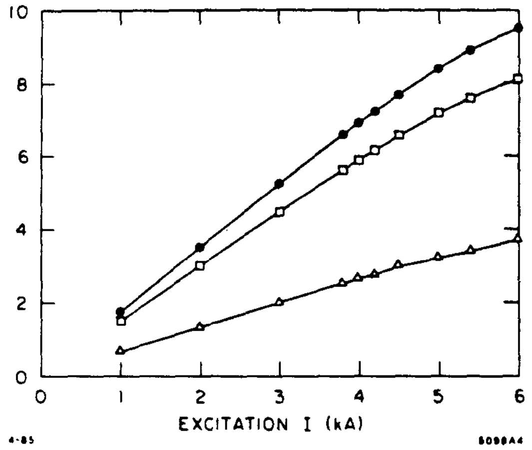

Fig. 4. The dipole (□, KG), quadrupole (•, KG/cm) and sextupole strength (△, KG/cm/cm) *vs.* I.

ANALYSIS OF THE MEASUREMENTS

If we look more carefully at the data around the 3982 A point, they are not necessarily within the tolerances we set for each components in the Sect. 2. Our method of characterizing the magnet consists of two steps. The first is to redefine the magnetic center line (MACL) at a position where the designed value of $K = B/G$ is reproduced. Then the second step is to calculate the required current adjustment to the excitation to bring dipole and quadrupole field to the designed values.

Each magnet has a mechanical center line (MECL) defined in relation to the upper and lower alignment grooves on the laminations. Typically the shift from the MECL to the newly defined MACL is about 2 to 3 mils which will be recorded and used in the actual alignment of the magnet in the tunnel. The magnitude of sextupole component after position shift and current adjustment has to be recalculated. Shown in Fig. 5 are the results of the above mentioned shifts, adjustments and sextupole deviations. The important number here is the range of current adjustments since it is not a free parameter for a string of magnets powered in series. The results show that the adjustment is about 1.8% for every magnet with a spread of less than 0.2% which is within the tolerance given in section 2.

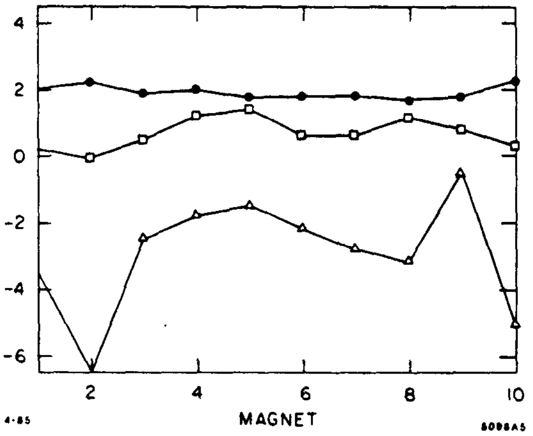

Fig. 5. The center line shift (△, mil), current adjustment (•, %), and sextupole deviations (□, %) for ten magnets.

Furthermore it is shown that the sextupole deviation after adjustment is well within the 5% tolerance.

Next we will look at the effect of gap variation. For our design a vertical translation of the poles opening the gap by, for example, 2 mils results in the decrease of 0.3% in dipole and 0.6% in gradient strength which has also been confirmed by a POISSON calculation. This calculation predicts the consatnt relating the gap deviation in mil to the current adjustment in percent to be 0.15. The constant derived from the least square fit to the measurement results as shown in Fig. 6 is 0.2.

A similar correlation plot between the center line shifts in micro meter and the gap deviations in mil indicates the constant is -42, while the calculation predicts -38. We conclude that there exist reasonable correlation between mechanical and magnetic measurements in a statistical manner and that correlation can be explained from the magnet design.

For a magnet with sagitta deviation of Δs, if the end points of the magnet and the coil are aligned, the resultant effect will be eqivalents to a parallel off-set of $\Delta X = 2/3 \times \Delta s$. Of the ten magnets shown in Fig. 5 the average sagitta is 111 mils and the RMS spread is 2 mils. The length, roll, and the height parameters of the magnets turn out to be the easier ones to satisfy. They are all within the tolerances set in Sect. 2.

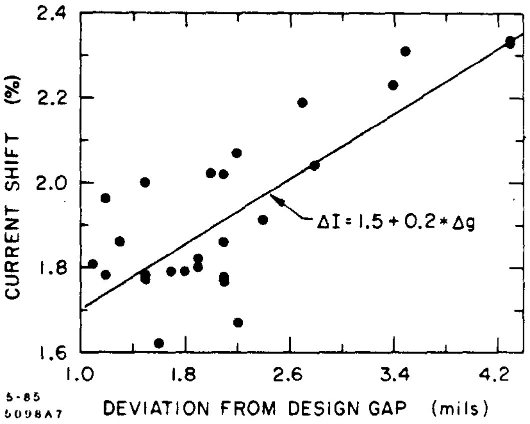

Fig. 6. The correlation between the gap deviation (Δg) and current adjustment (ΔI).

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