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SLC ARC TRANSPORT SYSTEM – MAGNET DESIGN AND CONSTRUCTION*

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This paper describes design and construction details of alternate gradient bending magnets, 950 of which are used in a single pass transport system to bring high energy positrons and electrons into head-on collision. The overall "arc" system is 8000 ft. long, has an aperture of 1/2" and a circumference factor of 96 %.

INTRODUCTION

A true electron linear collider, in which two linacs point at each other, does not require an arc system. The Stanford Linear Collider,[1] containing but one linac for both particles, requires a bending system to direct the particles at each other. To maintain high performance this bending must be designed to produce as little phase space dilution and energy loss as possible. Quantum effects in the synchrotron–radiation energy loss mechanism, coupled with finite amplitude (β) and dispersion (η) functions will cause some emmittance growth. For a given gradient in an AG structure, this growth is proportional to L^3/r^4, in which L is the length of each magnet and r is the bending radius. This speaks for a lattice of large radius containing many short very high-gradient magnets. In the adopted design, r is a site limited 279 meters, the guide field is 6 KG at 50 GeV with a corresponding gradient of 7 KG/cm. With a phase advance per cell of 108°,[2] the length of a magnet is 2.5 m, and the intermagnet drift is 10 cm.

Figure 1 depicts the overall geometry of the system. The numbers refer to sections which, in and of themselves, are second order achromats.[3] Each contains a train of 20 magnets and has a phase shift of exactly 3 π.

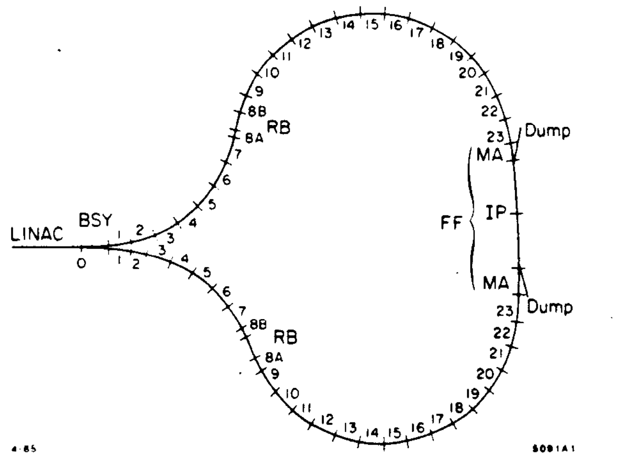

Fig. 1. Layout of Arcs to Interaction Point, (numbers refer to achromats).

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MAGNETIC FIELD SPECIFICATION

The lattice design calls for a combined function dipole, quadrupole and sextupole field distribution of the form:

$$B_y = B_{y0}\left[1 - \frac{n}{\rho}x + \frac{\beta}{\rho^2}x^2 + \ldots 0\right] \quad \text{for } y = 0\,.$$

The sextupole term in the expansion is there so that the achromats provide a momentum pass band of ± 0.5%. The "hard edge" fitted TRANSPORT values have been adjusted to account for "physical effective lengths" and are shown in Table I.

TABLE I

Dipole Field in KGauss	B_{y0}	= 5.96976
Bending Radius in Meters	ρ	=279.378
Field Index	n_f	=-32847.5
	n_d	=+32848.5
Field Gradient KG/cm at Equil. Orbit	g_{av}	=7.0189
Sextupole Terms:	B_s	$=1/2g'x^2$
in focusing magnet:		
	$\frac{\beta_F}{\rho^2}$	=+0.0013579 mm^{-2}
	g'	=-1.629 kG/cm^2
in defocusing magnet:		
	$\frac{\beta_D}{\rho^2}$	=-0.0022748 mm^{-2}
	g'	=-2.702 kG/cm^2
Eff. Arc Length of	L_b	=2.50300 m
Magnet ℓ	L_g	=2.48565 m
	iron L	=2.47935 m
1/2 cell arc length		2.596201936 m
Total Arc Cell Length		5.192402112 m
		=17.03544 feet
12 Cell Bend Angle		0.513323348°

TOLERANCES

Because the incoming phase space is miniscule (3×10^{-10} meter-radians) and the magnets contain high gradients, the aperture of the collider is only a few millimeters. This requires good correction of the central trajectory, not only so that the beam remain inside the vacuum chamber, but also that no otherwise avoidable emmittance growth take place either due to additional synchrotron radiation or higher order optical distortion. A distinctive property of an achromat composed of magnets having the above listed fields is that a transverse displacement will cause an orbit shift without introducing residual dispersion. Magnet misalignment errors will therefore be handled online via physical "magnet movers" using the beam's measured position as input. Extensive simulations using tracking programs[4] indicate that magnet to magnet survey errors of 100 microns rms and field gradient errors of 0.3% rms are correctable without substantially deleterious effects on the luminosity of the machine. These values therefore set the scale for all subsequent magnet construction tolerances.

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MAGNET PROFILES

The first published article on strong focusing[5] contains the concepts of a magnet suitable for the SLC arcs. Figure 2 depicts the adopted cross section with field lines as calculated by POISSON.

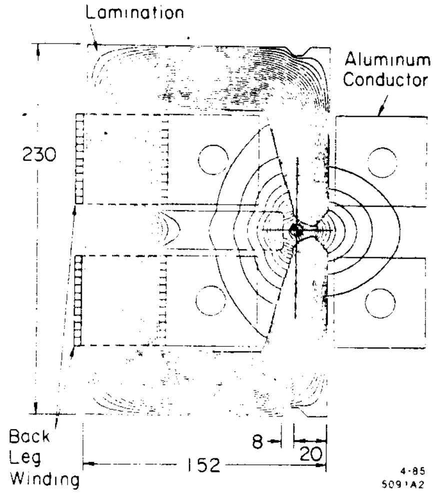

Fig. 2. Crossection of Alternate Gradient Arc Magnet, (Schematic).

The detailed design of the pole shapes was performed by optimizing the boundary contours in that geometry which is obtained by that conformal mapping[6] of the original geometry which transforms the combination of dipole, quadrupole and sextupole fields into a dipole field and then transforming the resultant back into the original real geometry. Figure 3 shows the field plot in "dipole geometry."

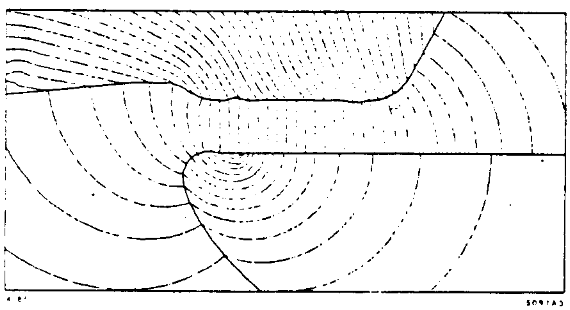

Fig. 3. AG Magnet Transformed into Dipole Geometry.

In order to dramatize the *differences* in pole shape that result from *opposite sign* sextupolar components, we have plotted final profiles "on top of each other" in Fig. 4. When mounted in the tunnel, one or the other magnet should be considered "reflected" about the beam axis. Since the value of B_Y should vanish at the edge of the neutral pole, one notes that the distance at which the beam rides with respect to this surface is different in the two cases. The so called characteristic length of this AG magnet, $k = B_0/g = 8.511$ mm is, for all practical purposes, the same in the two magnets.

CONSTRUCTION PARAMETERS

An analysis of capital construction costs in relation to operating power costs indicated the use of aluminum as a conductor material and a generous coil window. The width of the iron backleg was chosen so that the magnet would begin to show saturation effects only above the nominal operating level (50

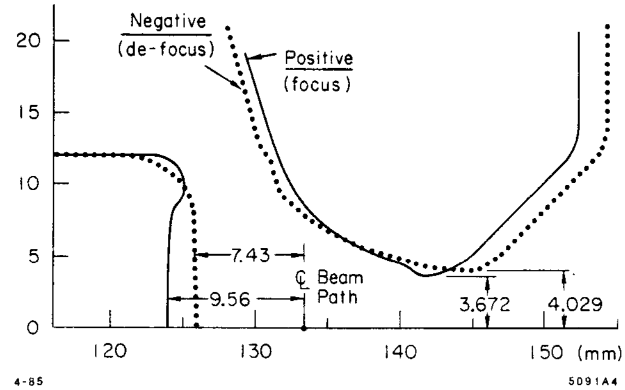

Fig. 4. Pole Profiles for Focus and Defocus AG Magnets.

GeV). The water velocity was designed to be low enough so that vibration levels were immeasurably small. Construction parameters are listed in Table II.

TABLE II. MAGNET PARAMETERS AT 50 GeV

Magnet designation		6AG2500
Number of Magnets		940
Field at 50 GeV	KG	5.9698
Field Integral at 50 GeV	KGm	14.9423
Gap Height		
a) at equilibrium orbit	mm	16.4
b) minimum focusing	mm	7.346
c) minimum defocusing	mm	8.057
Width of Good Field Region	mm	± 4.0
Core Length	mm	2479.353
Core Weight	lbs	1100
Lamination Width	mm	152.5
Lamination Height	mm	230.0
Ampere-turns/pole	Amps	3982
Turns/pole		1
Conductor Cross Section	inches	2.1990× 2.060
Conductor area	mm^2	2840
Cooling Hole Diameter	in	.375
Resistance at 55°C	milliohms	0.12
Power/Magnet	KW	1.65
Voltage Drop/Magnet	Volts	0.44
Current Density	$Amps/mm^2$	1.37
Coil Weight	lbs	158
Number of Water Circuits		4
Water Flow Rate/Magnet	gpm	0.59
Water Velocity in Each Conductor	ft/sec	3.5
Temperature Rise per Circuit	Degrees C	11.5
Trim Windings		
No. of Coils		2
Turns/Coil		28
Maximum Current Rating	Amps	5

FABRICATION TECHNIQUES

Steel : On the basis of experience with other open "C" magnets and trials with this shape, great care was taken in selecting the mechanical properties (i.e. uniformity and stampability) of the steel. About 900 tons of 16 gauge, cold rolled strip AISI 1005 steel (.06 ± .02% Carbon) were purchased. We believe that successful laminations resulted through strict adherence to the temper (No. 3) specification (Rockwell B scale 70 ± 5 pts) as well as tight tolerances on crown and thickness and the fact that the steel was rolled, slit and provided to the stamping house in straightened flat packages (not in coil form).

Laminations : The laminations were punched in a conventional single hit operation. It was found necessary to sharpen the die every 40K hits. One measure of the uniformity of laminations is the uniformity of the minimum gap dimension. Figure 5 shows the distribution of this dimension, measured with a "Lasermike[7]" device sampled on a 1% basis from the complement of over 800K defocus laminations. The "one sigma" value of the fitted normal distribution is 0.00049".

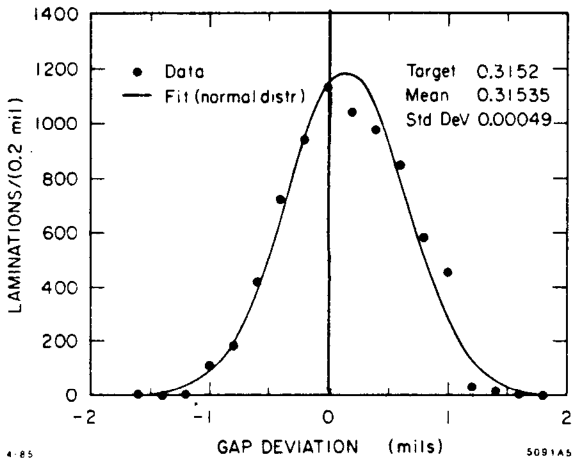

Fig. 5. Distribution of "gap" size errors.

Magnet Assembly Facility : The handling of over 1.6 Million laminations required space and the enforcement of QC and inventory procedures not normally found in a research laboratory setting. A 20,000 sq. ft building and a PC computer driven database control system were readied.

Stacking Fixture : The some 1600 laminations that comprise a magnet are stacked (nose down) on a fixture (one for each F or D type) which contains a central key and two accurately ground outer rails and then hydraulically pressed between two end plates. The guides have been so shimmed that when the magnet is removed and supported as if in service, it assumes its correct vertical straightness and horizontal beam following sagitta. 1/2" steel side, top and bottom plates are added. The upper seams are welded and allowed to cool. The lower weld is then made with an automatic seam tracking welder and the end plates fastened. Hydraulic cylinders press the magnet from its form. The production rate (using 2 fixtures) is 4 magnets per day. Figure 6 illustrates this process. A finished core, fitted out with main conductors, backleg windings and vacuum chamber is shown in Fig. 7.

Main Conductors : These magnets do not have coils in the conventional sense. Instead, the cores are strung on 4 heavy bus bars like beads on a string. Connections are provided every 4 cores or at 10 meter intervals since this is about as long a conductor that can be readily handled and transported. Each aluminum bar is machined for end connections and then hard anodized, painted with a conformal coating[8] and wrapped with a stiff layer of DMD[9] for insulation to ground. We estimate that this should provide a radiation and abrasion resistant insulation capable of holding off the highest working voltage (400 V.) with an initial safety factor of 8.

Backleg Windings : Particles traversing the arcs loose a substantial amount of energy by synchrotron radiation. For $E_0 =$ 50 GeV, $dE/E = -2.4\%$. Backleg windings are provided to

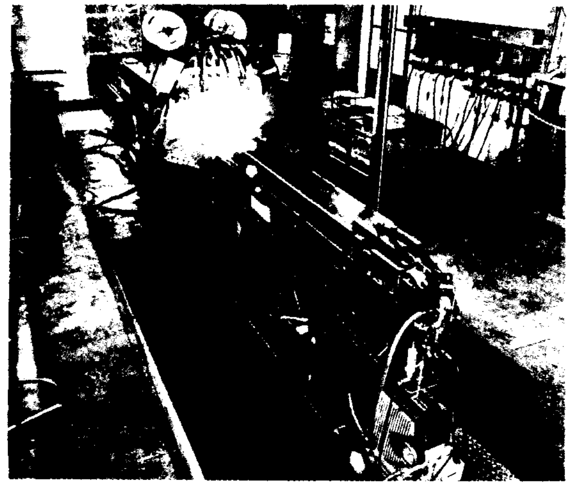

Fig. 6. Core fabrication by welding.

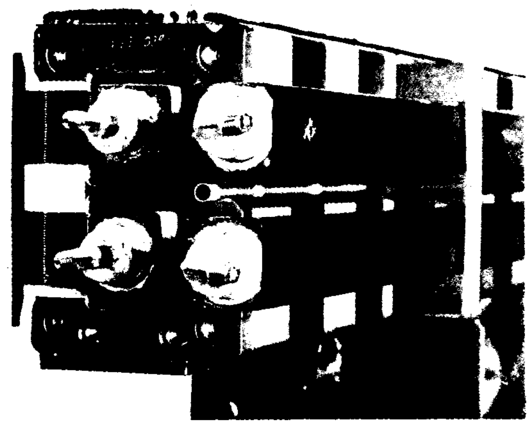

Fig. 7. Finished core showing conductors and vacuum chamber.

either buck or boost the main excitation windings by as much as $\pm$ 3% and will be used to provide a tapered correction on an achromat by achromat basis. These windings may also be used for other types of correction.

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