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FABRICATION AND TEST OF PROTOTYPE RING MAGNETS FOR THE ALS

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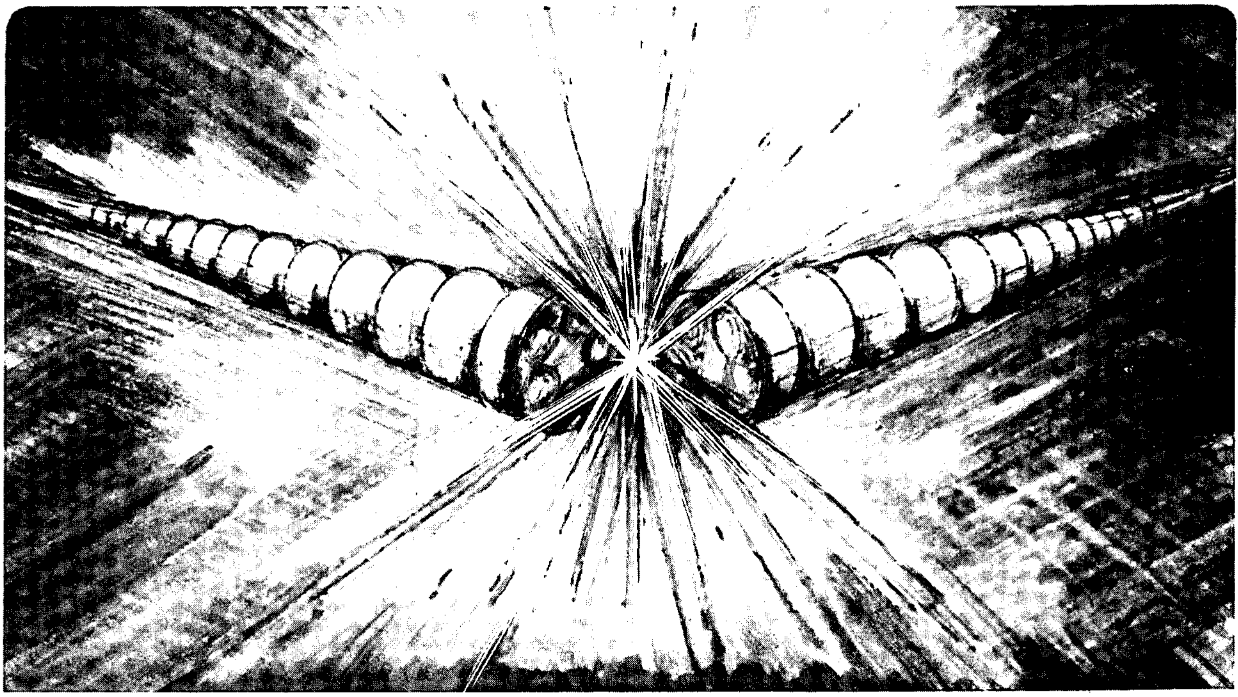

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DISCLAIMER

FABRICATION AND TEST OF PROTOTYPE RING MAGNETS FOR THE ALS*

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Abstract

Prototype Models for the Advanced Light Source (ALS) Booster Dipole, Quadrupole and Sextupole and the Storage Ring Gradient Magnet, Quadrupole and Sextupole have been constructed. The Booster magnet prototypes have been tested. The Storage Ring Magnets are presently undergoing tests and magnetic measurements. This paper reviews the designs and parameters for these magnets, briefly describes features of the magnet designs which respond to the special constraints imposed by the requirements for both accelerator rings, and reviews some of the results of magnet measurements for the prototype.

Summary

The Booster magnets are required to cycle between excitations required for electron energies of 50 MeV at injection and 1.5 GeV at extraction at a nominal rate of 1 hertz. The coil insulation systems are designed for voltages required for future possible operation up to 10 hertz. In order to avoid eddy current induced core heating and minimize the effect of material coercive force on the residual field at the low fields required at injection, 0.025 inch thick M36 Silicon Steel sheet with C5 insulation is selected for the core laminations.[1] The coil parameters are chosen to match reasonable power supply requirements for all frequency options.

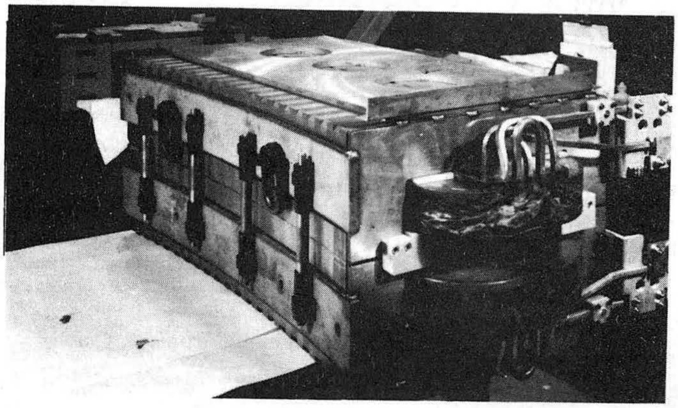
The Storage Ring magnets must cycle between excitations required for operation between 1.0 and 1.9 GeV in acceleration times which are measured in minutes. The core material selected for the Storage Ring Magnets is low carbon, annealed and uninsulated steel sheet, 0.060 inch nominal thickness. The selected thickness was based on past experience which indicated that 0.060 inch is the maximum thickness which can be easily and reliably stamped with good control on the stamping burr. The coils were designed to match reasonable power supply requirements. All the Storage Ring magnets have a "C" type configuration in order to accommodate a vacuum chamber which must provide substantial photon beamline clearances.

All the laminations for all the magnets are sorted in order to provide magnet to magnet reproducibility, top to bottom and end to end symmetry. In the case of the Booster magnets, whose laminations have symmetry about a vertical centerline, the laminations are flipped in order to provide left to right symmetry. Selected parameters for the various magnets are summarized in Table 1.

Booster Dipole [2]

The Booster Dipole is a split H type magnet with flat pancake coils as shown in Fig. 1. The core is curved to follow the electron beam trajectory in order to minimize the stored energy and power requirements. The laminated cores are of welded construction using heavy curved bars captured in the sides of the laminations. The side bars and cover plate are lightly welded to the laminations to achieve the required core mechanical dimensions and to provide the magnet support. Prior to the core stacking, the end contours are step punched, stacked and epoxy impregnated into 5 cm long blocks. The water cooled coils are designed for 3 kV operation at 10 Hz.

Magnetic measurements were carried out at DC, 2 Hz and 10 Hz.[3] At the 1.248 Tesla design field, DC measurements give a magnetic efficiency of 98.9% and an effective field length of 1.045 m. Longitudinal variation in the gap due to the core clamping results in field variations of 10^{-3} Tesla along the length of the magnet. An increase in the effective entrance/exit angles of 0.55 degrees was due primarily to a 0.0125 T/m gradient observed in the magnet gap. An integrated sextupole of 2.13 T/m was measured which comes primarily from the ends. AC magnetic measurements showed similar behavior. Thermal measurements at 10 Hz showed a 14° C maximum core temperature rise with a 7 hour time constant.



CBB 886-6351

Fig. 1. Booster Dipole Prototype

Booster Quadrupole [4]

Two different lengths for the QF and QD families are required. The core is made from two glued and bolted core sections assembled around the vacuum chamber. The pole geometry uses the contour developed for the Storage Ring Quadrupole. The coils are wound from 0.340 inch square hollow Copper conductor.

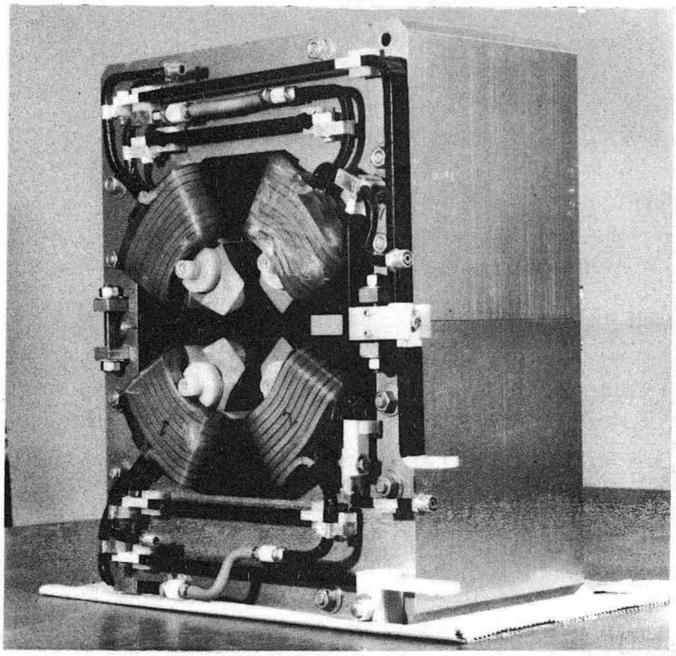


Fig. 2. Booster Quadrupole Prototype CBB 889-8663

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Magnetic measurements were performed for the prototype QF.[5] The harmonic content of the line integral of the field, measured at the excitation required for 1.5 GeV operation, normalized to the fundamental at 3 cm reference radius, is summarized in Fig. 3. Also shown is the reconstruction of the multipoles into an iso-error curve. Note that the largest error is the "allowed" n=6 harmonic. Harmonic measurements were also made after intentionally displacing the core halves with respect to each other to determine the effect of assembly errors. These measurements matched theoretical predictions[6] quite well. Harmonics due to assembly errors are quite small.

n	$\frac{B_n}{B_2}$	ϕ_n
	$1{:}10^{-2}$	deg
3	.045	-87.8
4	.077	-2.7
5	.014	-74.3
6	.185	-0.5
7	.001	42.0
8	.010	-27.1
9	.008	-147.0
10	.079	179.3
11	.004	-121.3
12	.014	-148.3
13	.004	84.4
14	.025	-110.1

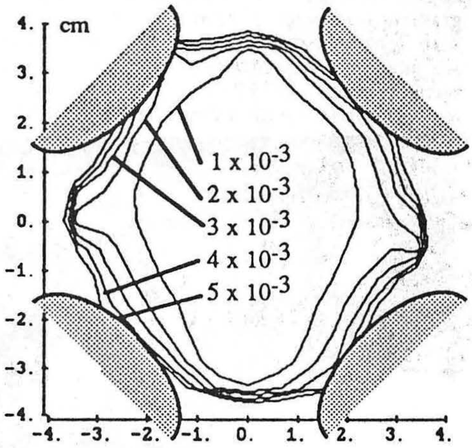
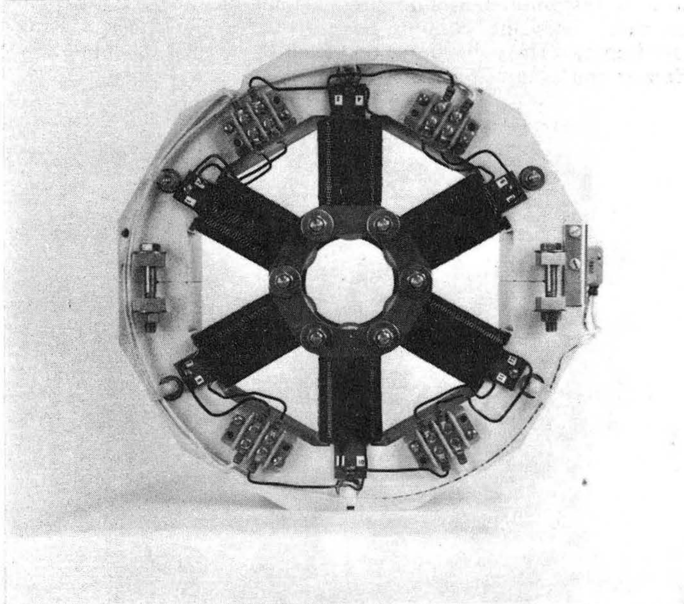


Fig 3. Booster Quadrupole Harmonics and Iso-Error Curves

Booster Sextupole [7]

Twenty identical magnets are divided among SF (12 magnets) and SD (8 magnets) families. The core is made from two glued and bolted core sections assembled around a vacuum chamber. The pole geometry, optimized in dipole coordinate space for the Storage Ring quadrupole, was transformed to the sextupole coordinate space. The coils are wound from #13 square solid Copper conductor and are cooled by natural convection.



CBB 8810-9522

Fig. 4. Booster Sextupole Prototype

The harmonic content of the line integral of the field measured at 6 Amps, normalized to the fundamental at 3 cm reference radius, is summarized in Fig 5.[8] Also shown is the reconstruction of the multipoles into an iso-error curve. The largest error is the "allowed" n=9 harmonic.

n	$\frac{B_n}{B_3}$	ϕ_n
	$1{:}10^{-2}$	deg
4	.033	-149.9
5	.034	-130.3
6	.015	68.5
7	.014	-38.0
8	.024	95.5
9	.374	173.8
10	.043	-12.5
11	.034	82.9
12	.009	-130.1
13	.031	-12.8
14	.078	-121.3
15	.048	-27.6

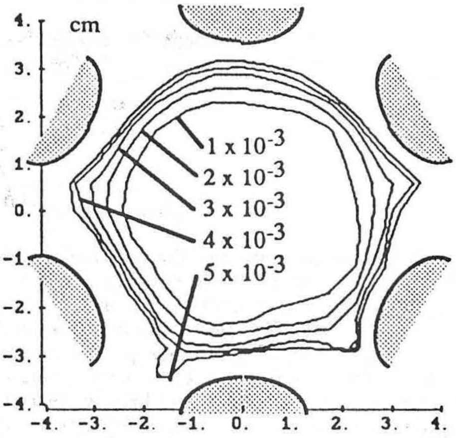


Fig. 5. Booster Sextupole Harmonics and Iso-Error Curves

Storage Ring Gradient Magnet [9]

The core for the Gradient Magnet, whose pole provides a field which combines a bending and focusing component, is made in one piece. The beam orbit through this magnet, built with a straight rather than curved core, describes a hyperbolic cosine curve rather than a curve with uniform radius of curvature. It was felt that the cost and precision core assembly advantages of a straight core were well worth the beam orbit implications for this geometric concession.

The prototype for this magnet has been built and will be thoroughly measured. Part of the magnetic measurement program will include machining a removeable insert at the pole end to adjust some of the harmonics due to the three dimensional end fields.

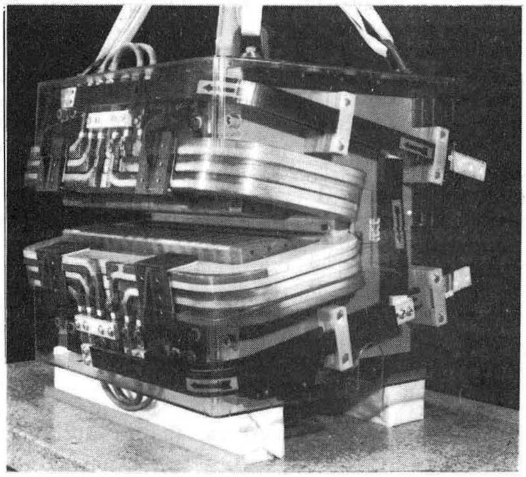


Fig. 6. Storage Ring Gradient Magnet Prototype CBB 8112-11882

Storage Ring Quadrupole

Twenty-four magnets each of the QFA, QF and QD families are required. All three magnet families share the same lamination cross section but have different core lengths. The pole end was optimized using MIRT[10] (one of the POISSON family of two-dimensional magnetostatic codes) in the dipole coordinate space and transformed to the quadrupole space.[11]

The QFA magnets are connected in series and thus use a 0.340 inch square hollow copper conductor which requires a fairly high current. The QF and QD magnets, on the other hand, are used to tune the orbit around the insertion straight sections for the Storage Ring, are thus powered in pairs and use a smaller 0.169 inch square hollow conductor. A QFA prototype magnet is being assembled and will be carefully measured. Part of the magnetic measurement program will include machining a removeable insert at the pole end to adjust some of the harmonics due to the three dimensional end fields.

Storage Ring Sextupole [12]

The requirements for the Storage Ring sextupole and the constraints imposed by the requirements of the vacuum chamber had a profound affect on its design. The core is divided among three segments (two of which are identical) in order that the magnet can be assembled around the vacuum chamber.

Because space constraints around the ring did not allow for a large number of correctors, this magnet is required to provide horizontal and vertical steering and skew quadrupole fields in addition to the fundamental sextupole field. These fields are excited by trim coils around each pole. Each trim coil has two sets of windings, wound with solid square conductor. The windings are cooled by conduction to a water cooled circuit connected to a Copper sheet imbedded in the winding with high thermally conductive epoxy. The sextupole field is provided by coils wound with conventional .340 inch square hollow copper conductor.

The poles are asymmetric about their centerlines at a radius beyond three times their pole radius, in order to provide adequate room for the coils and for the vacuum chamber and to avoid iron saturation when all coils are excited The vacuum chamber also required a narrow pole tip and the pole contour resulted in substantial "allowed" harmonic errors.[13] Fortunately, the allowed harmonics for the sextupole geometry have a high index (≥ 9) so their fields damp out quickly at a small radius.

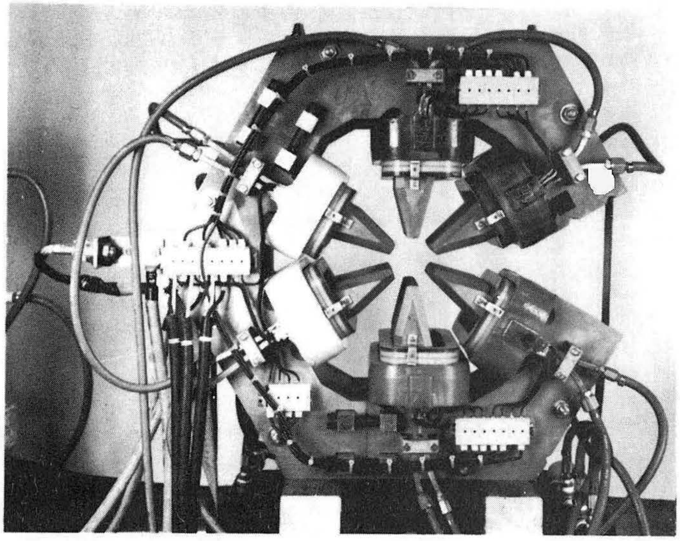


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Fig 7. Storage Ring Sextupole Prototype.

Magnet	No.	Field/Gradient	Gap (mm)	Conductor Description (Dimensions in inches)	Current (Amps)	Resistance (mΩ)	Inductance (mH)
Booster Parameters @ 1.5 GeV							
Booster Dipole	24	B = 1.248 T	44.0	.485" Sq x .2750" ID hole Hollow	746	29.5	20.4
Booster Quadrupole QF	16	B' = 15.91 T/m	32.5	.340" Sq x .1835" ID hole Hollow	418	17.7	2.4
Booster Quadrupole QD	16	B' = 16.37 T/m	32.5	.340" Sq x .1835" ID hole Hollow	430	13.8	3.7
Booster Sextupole	20	$\frac{B_P}{r_0^2} = 55.5$ T/m²	35	#13 (.076 inch square) solid Cond.	4.8	1450	145
SR Parameters @ 1.9 GeV							
SR Gradient Magnet	36	B = 1.354 T B' = 5.193 T/m	50.0	.640" Sq x .3200" ID hole Hollow	924	14.9	17
SR Quadrupole QFA	24	B' = 19.1 T/m	32.5	.340" Sq x .1835" ID hole Hollow	507	34	5.6
SR Quadrupole QF	24	B' = 17.0 T/m	32.5	.169" Sq x .0920" ID hole Hollow	110	398	66
SR Quadrupole QD	24	B' = 17.0 T/m	32.5	.169" Sq x .0920" ID hole Hollow	110	248	38
SR Sextupole	48	$\frac{B_P}{r_0^2} = 500$ T/m²	35	.340" Sq x .1835" ID hole Hollow	395	20.3	3.6
Horizontal Bend	48	B = 0.07 T		#13 (.076 inch square) solid Cond.	22.7	2765	
Vertical Bend	48	B = 0.07 T		#13 (.076 inch square) solid Cond.	18.9	2765	
Skew Quadrupole	48	B' = 0.75 T/m	35	#13 (.076 inch square) solid Cond.	15.4	672	

Table 1. Selected Parameters

[1] J. Milburn, J. Tanabe, "Residual Field in Booster Ring Magnets", Engr. Note. M6697, March, 1988.

[2] E. Hoyer, "Booster Dipole Magnet Design Calculations, LBL Engr. Note M6673, [LSME-37], December, 1987.

[3] R. Keller, etal, "Measured Properties of the ALS Booster Synchrotron Bending Magnet Engineering Model, ESG Tech. Note 105, [LSAP-61], February, 1989.

[4] J. Milburn, "Booster Quadrupole Design Calculations", Engr. Note M6687B, [LSME-146], April, 1988.

[5] J. Tanabe, etal, "Booster Quadrupole Magnet Measurement Summary", Engr. Note M6787, [LSME-133] December, 1988.

[6] K. Halbach, "First Order Perturbation Effects in Iron Dominated Two Dimensional Symmetrical Multipoles, Nuclear Instruments and Methods, Vol. 74 (1969) No. 1, pp. 147-163 and LBL Report, UCRL-18841, April, 1969.

[7] J. Tanabe, S. Marks, K. Luchini, "Booster Sextupole Design Calculations", Engr. Note M6816, [LSME-156], March, 1989.

[8] S. Marks, J. Tanabe, K. Luchini, "Summary of Magnetic Measurements for the Booster Sextupole Prototype", presently written but unpublished, March, 1989.

[9] J. Tanabe, "Storage Ring Gradient Magnet Design Calculations", Engr. Note M6790, February, 1988.

[10] K. Halbach, "A Program for the Inversion of System Analysis and its Application to the Design of Magnets", Proc. of the Int. Conf. on Magnet Technology, p. 47, 1967.

[11] K. Halbach, "Application of Conformal Mapping to Magnets with Non Linear Iron", Vol. 64, p. 278, 1968.

[12] S. Marks, "Multipoles for the ALS Storage Ring Sextupole", Engr. Note M 6599A, December, 1987.

[13] S. Marks, "Design Calculations for the Storage Ring Sextupole", Engr. Note M 6671, November, 1987.

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