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Evaluation of Matched Superconducting Dipoles

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Abstract

Two superconducting Dual Dipole magnets have been measured at ac and dc excitations up to fields of 540 GeV equivalent proton energy in the present NAL Main Ring. Apart from a quadrupole term of as yet undetermined origin, the measured quality of field on the midplane, $\Delta B/Bo$, is consistent with the homogeniety requirements specified for these magnets. Additional field measurements and operational evaluation of magnet performance in a high radiation environment are being undertaken.

Introduction

Progress towards design of an Energy Doubler accelerator for the NAL Main Ring has been made by fabrication and testing of a series of small models culminating in magnetic testing of a matched pair of 29 inch long shell geometry dipole magnets. Known as the "Dual Dipoles", they were built to determine whether two superconducting magnets of a design being considered for the Energy Doubler could be made identical enough in vital characteristics to enable construction of a working accelerator. To this end the critical tests of pulsing both magnets simultaneously to determine their ac tracking properties and of measuring harmonic content of the dipole fields have been completed.

Construction

The magnets are wound in concentric shells with the superconductor placed to best approximate a cos θ current distribution. Design criteria for the wire placement required minimizing the sum of all harmonics up through the 22nd pole. Magnet characteristics are summarized in Table I. Coils are bonded to the bore tube and held against magnetic pressure forces by banding with 150 turns of 0.375 inches wide by 0.010 inch thick mylar tape. Longitudinal spacing between bands is 0.250 inches. By also using part of the mylar banding as a spacer between the inner shell and outer two shells, percolation cooling channels are provided throughout the windings so at least 40 percent of one narrow face of each turn is exposed to liquid helium. These are the first magnets at NAL that use graded conductor in the windings; that is, the distribution of superconducting wire throughout the coil is adjusted for critical current of the wire so that wire of lower characteristic I_c is used in lower field regions. This has the promise of saving up to 25% in conductor costs over that of magnets using single I_c wire throughout. Projected design for the final 20 foot Doubler magnets required very high current density wire, 55 kA/cm^2 and 75 kA/cm^2; however, in order to expedite the magnet development program older, lower current density wire was used. Consequently, the maximum field in the bore of the Dual Dipoles is limited to 2.7 T and a full field test of the suspension and banding systems could not be accomplished in this program. The higher current density wire is now on hand, and twenty

foot Doubler prototype magnets are being built from it.

The magnet is held rigidly in its helium container by epoxy fiberglass G-10 spacers. This container forms the inner wall of the vacuum dewar and is held in place by a bicycle wheel type suspension system. The suspension "spokes" were wound with epoxy impregnated DuPont PRD-49 fiber. The suspension must repond with a net restoring force to displacement forces generated between the windings and iron shield when their respective axes are not coincident. Radiative thermal losses were reduced by winding 75 layers of super-insulation (aluminized mylar) around the helium jacket between the bicycle suspensions. Super-insulation was also interwoven between the spokes of the suspension. In the doubler the inner wall of the helium container, to which the windings are banded, will also form the wall of the evacuated beam tube. Because lab testing is facilitated by having ready access to the magnet bore, a 2" ID warm bore tube wrapped with 10 layers of super-insulation was installed before evacuating the cryostat. While this provides a slightly higher heat load it did not affect operation of the magnet.

Warm Testing - Quality Control

At the end of each stage of production the magnet coils were tested for shorts by ringing. Some layer to layer shorts were discovered as shells were being assembled onto the bore tube, but these were easily corrected and no further shorts observed. To verify the quality of insulation, hi-potting between coil and ground was done to a peak of 1500 volts at room temperature with no noticeable leakage current. Before sealing it in the dewar, the coil was fully instrumented with voltage taps and temperature sensing carbon resistors. Measurements were also made at room and liquid nitrogen temperatures of resistance and inductance. These results confirmed the values reported in Table I.

Superconducting Operation

A general block diagram of the Dual Dipole operating system is shown in Figure 1. The power supply, an NAL standard Transrex 500-5, produces significant ripple and SCR noise necessitating the L section filter made with the Main Ring B_2 magnet and 80 millifarad capacitor bank. Operation of the

Dual Dipoles, which can be powered separately or in pairs, is the same as for conventional magnets up to a point. Turn on, turn off and other changes of current must be limited in rate or the magnet will quench, and when quenches do occur provision must be made for safely dispersing the energy stored in the magnetic field. It should be pointed out that the extraordinarily high quality thermal insulation necessary for normal operation means that most internally generated heat cannot be dissipated once the liquid helium is blown off. To dump the energy safely a sensitive voltage comparator differentially monitors the superconducting magnet and shuts off the Transrex when a resistive voltage develops across the magnet, indicating a quench. The collapsing field then introduces an emf of opposite polarity to the Transrex, forward biasing the shunt diode which is outside the dewar, and dumping the energy into a stainless steel load resistor.

During normal operation liquid Helium level is continuously monitored and automatically controlled via an in-line solenoid valve described previously.[1] Ramping of the magnets is accomplished by programming the Transrex with a voltage signal resembling a standard Main Ring current waveform and derived from a commercial waveform generator and special shaping circuits.

Cooldown is initiated by passing liquid nitrogen directly into the dewar. By using the temperature dependence of the resistivity of the coil, the magnet is made to act as its own temperature sensor. At about $100^{\circ}K$, before reaching thermal equilibrium with liquid Nitrogen, the nitrogen is thoroughly purged with helium gas. After a slight warming to ensure removal of all nitrogen, cooldown is continued with liquid Helium. From a warm start the entire drill requires less than three hours.

Magnet Performance

DC performance characteristics are reported in Table II. The maximum currents shown were reached only after much training, the process of attaining successively higher quench currents by repeated excitation of the magnet to the maximum current it will take. For the Dual Dipole four or five quench cycles at the start of each run were required to reach a constant maximum current. The training effects tended to be remembered in spite of

recycling of the magnets to room temperature and so at the end of the test series both magnets were operating considerably closer to the short sample limits of the superconducting wire than in the beginning.

The ultimate limit for operation is set by short sample tests of the superconducting wire for critical current versus critical field at about $4.2^{\circ}K$, the approximate temperature of the pool boiling Helium used to cool the Dual Dipoles. Practical operating limits are set by problems such as the 20% higher magnetic fields seen by the end coils that reduces critical current and the necessity, in the small geometry of the Doubler style magnet, of making extra short splices of the superconducting wire. With this latter problem in mind, special care was taken during manufacture to hold down, shunt with copper, heat sink and instrument all splices. During operation no voltage was observed across the splices to within the lower limits of our apparatus, $1 \mu V$. The magnet could be ramped continuously at a 15 second cyclic period to 85% of its dc critical current and reached a maximum dc current equal to 90% that of the smaller conductor as measured in a two dimensional cross section of the coil. This exceeds the design limits of 80% of short sample set for the Energy Doubler.

The transfer constant for each magnet was measured with a Varian NMR probe system and Hewlett Packard precision counter. Constants of the two magnets agree to within .16% of each other and to within .20% of the theoretically predicted values as reported in Table II. These values are an upper bound limited by the accuracy of the measurement.

Magnetic Measurements

The small bore of these magnets and relatively large size of most precision magnetic measurement probes prevents adequate direct field mapping. Consequently, one must measure the harmonic content of the midplane with appropriate search coils and reconstruct the field shape from this data according to the relationship

$$B(r, \theta) = B_0 \left(1 + \sum_{n=2}^{\infty} a_n \, r^{n-1} \cos(n\theta + \alpha_n)\right)$$

where the a_n are measured ratios of the higher order multipoles to the fundamental dipole. Two methods were used. In the first a coil is rotated at constant

angular velocity and the output waveform fed into an electronic wave analyzer.
The second method employs wire configurations uniquely sensitive to each
harmonic of interest. As a rough check of these two techniques a transverse
sweep with a Hall detector was made across the horizontal midplane of the
bore of one magnet. The accuracy of data obtained with the Hall probe was
only sufficient to allow a fit to a quadrupole field component which agrees
reasonably well with the quadrupole term determined by the other two tech-
niques.

Rotating Coil

The use of a rotating coil to measure magnetic fields is well known,[2]
such devices have been built at SLAC[3,4,5] and at NAL[6] to determine the
harmonic content of magnets. The NAL device was debugged as part of the
Dual Dipole testing and several problems discovered and corrected. In
particular, a large systematic error contributed by the mechanics of the first
rotator assembly introduced abnormally large quadrupole and sextupole
signals unrelated to the magnet under measurement. A second rotator solved
this problem.

Coil output was coupled to a Quantech Model 2449 wave analyzer which
measured the RMS value of the voltage at the harmonic frequencies correspon-
ding to the higher order magnetic multipoles. No attempt was made to determine
the phase angle of the higher order terms since the wave analyzer introduced
a frequency dependent phase shift on the output signal which is reconstructed
from the detected input harmonic. If this problem can be corrected or com-
pensated, phase angles should be readily obtainable from this apparatus.

The system was checked for calibration as follows. A square wave
of known frequency and amplitude was fed into the Quantech and the relative
harmonic values were compared to the mathemactical Fourier analysis for
the square wave. Significant departures from predicted values did not appear
until after the 11th harmonic (22 nd pole) which is well above that of present
interest. The whole system was tested for instrumental error by rotating
the coil in a Varian laboratory standard magnet. This magnet was previously
mapped with an NMR probe and showed a variation in magnetic field of less
than 50 mG over a 2" region at a field of 7 kG. The results of this test are
presented in Table III.

Since the pickup coil is only one inch long, measurements were made all along the axis of the magnet by mounting the rotating coil device on a lathe bed. Results obtained with this device are presented in Table IV. The average value for the central uniform region of the coil is presented. The midplane variation of field $\Delta B/B_0$ vs. the radial distance from the center is plotted in Figures 2 and 3 for all the multipoles measured <u>except</u> the quadrupole. The phase angles for each term are assumed to be those of the Snowden prediction which is also plotted in these figures. Addition of the quadrupole term will skew the field plot with respect to the x axis.

"Stationary" Harmonic Analysis

Harmonic measurements were also performed using a coil wound with turns placed in simple cos $n\theta$ approximations to the multipole of interest. The coil design is based on the work of Morgan[7] and the Sampson group at Brookhaven. Spacing restrictions on our 1" diameter coil, required by the extra small warm bore of the doubler magnets, limited the coil to two dipole, a quadrupole, sextupole and decapole windings.[8]

Measurement of a harmonic consists of rotating the coil through 360° in 8° steps. The output of the harmonic coil of interest is then run through a precision integrator and converted to a digital value in a Fluke 8200 DVM, which can resolve 1 μV. At the end of each 8° incremental rotation the DVM value and angle are recorded. The tabulated function so generated represents the incremental flux intercepted by the coil from 0 to θ. A perfect cos $n\theta$ winding will see no lower order harmonics, no higher order harmonics of even multipoles and small amplitudes of odd multipoles of the design harmonic. In an attempt to get larger voltages from the small, 1.25 cm, radius coil, the windings were made with a cable-laid 7 strand wire which was interconnected to give 7 turns for each harmonic coil. Unfortunately, this is a difficult mechanical assembly and resulted in considerable dipole pickup on all coils. The data could still be used by Fourier analyzing the measurements for each harmonic coil and extracting appropriate amplitudes and phase angles. The amplitudes extracted are then adjusted for radius and compared to those obtained from the rotating coil. The data and comparisons are shown in Table IV and a reconstruction of the deviation from a dipole field, again excluding the quad-

rupole data, is again shown in Figures 2 and 3 with the phase angle assump-
tion used before.

As can be seen in Figures 2 and 3, the measurement shows that the
worst deviation from a pure dipole on the midplane is ±6 parts in 10^4 - again
excluding the quadrupole component. Both measurements confirm this. The
computer predictions tended towards a better chromaticity closer to the
center of the bore while their large radius characteristic deteriorated much
more rapidly. These magnets appear to be of a quality that would yield a
chromaticity similar to the present Main Ring.

Figure 4 is a plot of the central dipole field as a function of the
distance along the central axis. This data was measured by two methods,
first with a hall probe and then with the rotating probe. The data for the
rotating probe is the relative dipole field only.

As can be seen from the data in Table IV, a large quadrupole term
was observed. Measurements with the 24" stepped harmonic have shown
that roughly 20% of the quadrupole amplitude can be attributed to a magnetized
seam weld on the stainless steel warm bore tube. For the moment the source
of the quadrupole is not known and investigation is continuing to find the cause
and eliminate it.

Tracking Tests

In order for accelerator magnets to be dynamically useful, their fields
must reproduce from magnet to magnet and from pulse to pulse. That is to
say, at any current and current ramp the ratio of fields of any two magnets
is a constant. To measure the tracking of the Dual Dipoles the circuit in
Figure 4 was used. Long pickup coils, matched mechanically, were placed
in each magnet and connected so that their outputs bucked. Further improve-
ment of the match was accomplished by rotating the coils with respect to
their mutual axis for a minimum output while exciting the Dual Dipoles with
a low amplitude 60 Hz signal while the magnets were warm. The actual test
was accomplished by integrating the difference signal and displaying this on
an x-y recorder against the integral of only one of the pickup coils. This gave
a plot of differentual flux vs. total flux, $2(\Phi_A - \Phi_B) / (\Phi_A + \Phi_B)$. Because

the match between the pickup coils was not perfect the resultant display is a line of positive slope, the linearity of which represents the match of the two magnets. In order to quantitatively measure the tracking difference between the two dual dipoles, each of the output curves was fitted by least squares method to the linear expression:

$$\Delta\Phi = a + b\Phi, \text{ where } \Delta\Phi = \Phi_A - \Phi_B.$$

The residuals, which show the departure from linearity, then give a quantative measure of dynamic tracking. After folding in the integrator gains and recorder sensitivities, one can set an upper limit on the mismatch of $\sim$ 5 parts in 10^4. This data, taken for 100, 50 and 30 second cycles is summarized in Table V. One could attempt to model and fit higher order terms in Φ to show the form of the departure from linearity. However, since the magnitudes of the residuals are approximately the same as the effects we are examining, it did not seem worth further investigation. The average residual is then a measure of the error bandwidth and sets an upper limit on tracking error.

Summary

The tests reported above mark completion of a necessary stage of development towards a working Energy Doubler dipole. They have shown that two magnets can be constructed with dc and ac excitation characteristics sufficiently alike to be used in an accelerator. Ramp rate sensitivity of the preliminary superconducting wire indicated no cause for concern about the wire to be used in the 4.5 Tesla, 6 meter Doubler dipoles. Further refinements in calculation of wire placement as a result of chromaticity requirements for the Energy Doubler accelerator will have to be undertaken but these magnets, apart from the apparently anomolous quadrupole component, meet the specifications put on them - namely, field homogeneity to < 1 part in 10^3 at 70% of coil radius.

Further modeling studies are scheduled only on full scale prototype magnets wound with the final conductor. In addition to repeating field quality and operational performance measurements, future tests will determine energy loss per cycle due to ramping of the magnetic field and other cryogenic losses. An important part of the continuing program will be the testing at

full field of the cryostat suspensions and the magnet banding system since
the present tests have only loaded them to one quarter of their specified
value.

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References

1. "A Magnetically Operated Cryogenic Valve", M. A. Otavka, B. P. Strauss,
   R. W. Fast, Advances in Cryogenic Engineering, Vol. 16.

2. Rawson-Lush rotating coil gaussmeter, manufactured by Rawson-Lush
   Instrument Co., Inc., Acton, Massachusetts.

3. "Spectroscopy of Quadrupole Magnets", J. Cobb and R. Cole, SLAC-PUB-
   133, Sept. 1965.

4. "Determination of the Quality of Multiple Magnets", J. Cobb, A. Robb, and
   D. Jensen, SLAC-PUB-313, June 1967.

5. "A New Precision Measurement System for Beam Transport Type Magnets",
   J. Cobb and D. Horelick, SLAC-PUB-750, May 1970.

6. "A Rotating Coil Device for Harmonic Analysis of Magnetic Fields",
   R. Juhala and G. Michelassi, NAL TM-455, Nov. 6, 1973.

7. "Stationary Coil for Measuring the Harmonics in Pulsed Transport Magnets",
   G. H. Morgan, Proceedings of the 4th International Conference on Magnet
   Technology, 1972; USAEC, CONF-720908; also Brookhaven National
   Laboratory paper BNL 17196.

8. "Stepped Motion, cos $n\theta$ Wound Pickup Coils for Harmonic Analysis of
   Magnetic Fields", B. P. Strauss and D. F. Sutter, National Accelerator
   Laboratory Technical Memo # TM-457, January, 1974 (to be published).

Table I

DUAL DIPOLE MAGNET PARAMETERS

NATIONAL ACCELERATOR LABORATORY **ENGINEERING NOTE**	SECTION Energy Doubler	PROJECT	SERIAL-CATEGORY	PAGE
SUBJECT "DUAL" DIPOLE MAGNET		NAME Bruce Strauss		
		DATE July 13, 1973	REVISION DATE	

Type	Concentric Shells - Cosine θ
Design Field	38,714.66 G
Transfer Constant w/ Shield	14.75 G / A
Field Tolerance	± .07% at r/ro = .7
Stored Energy at Full Field	10.735 kJ
Inductance	3.11 mH
Internal Diameter of Windings	2.16 inches
Useful Diameter	1.75 inches
Overall Length of Windings	30 inches
Steel Radius	3.050 inches
Terminal Current at Full Field	2625
Current Density in Wire at Full Field	
Conductor Type 1	39.4 kA/cm^2
Conductor Type 2	72.9 kA/cm^2

Construction Data

Coil #	θ start (^{o})	θ end (^{o})	r_{inner}	r_{outer}	No. turns	Conductor Type
1	0	79.64	1.08	1.24	22	1
2	0	48.49	1.29	1.41	20	2
3	0	44.78	1.41	1.52	20	2
4	70.42	79.64	1.29	1.45	3	1

Conductor Characteristics	# 1	# 2
Manufacturer	MCA	MCA
Filaments	1345	361
A_{sub}/A_{sc}	2:1	1.25/1
Substrate	Cu	Cu
Filament Size	47μ	75μ
S.C. Alloy	NbTi	NbTi
Twist	1/inch	1/inch
Overall Size (in.)	.150 x .075	0.122 x .056
Insulation	Formvar	Formvar
Minimum Short Sample	2250 @ 5 T	1250 @ 5 T
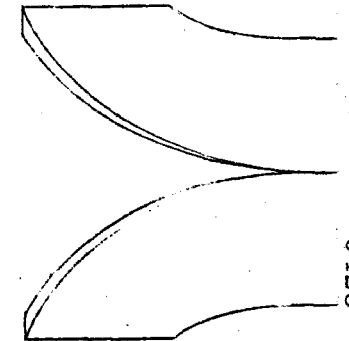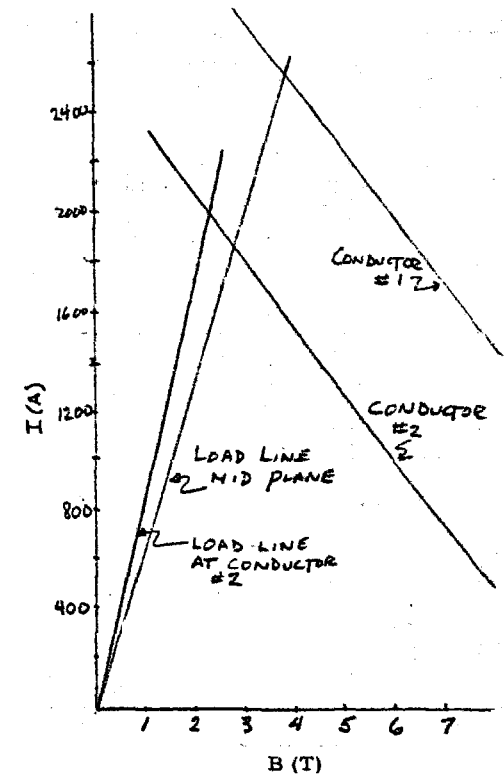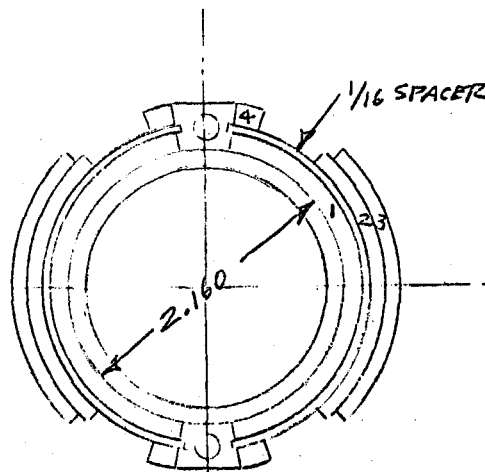
Table II

MAGNET PERFORMANCE

Maximum Current	1620 A
Maximum Field at Center	23,959 G
Transfer Constant with Shield	
Right side	14.785 G/A
Left side	14.809 G/A
Predicted	14.75 G/A
Relative Difference of Transfer Const.	0.16%
Relative Difference to Prediction	0.20%
Maximum Current Density in Wire	
Conductor 1 (.150" x .075")	22.32 kA/cm^2
Conductor 2 (.122" x .056")*	36.75 kA/cm^2

* Maximum central field limited by their "off the shelf" wire

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Table III

INSTRUMENTAL ERROR OF ROTATING
HARMONIC COIL

	Relative Amplitude to Dipole
2θ	7.33×10^{-4}
3θ	2.76×10^{-4}
5θ	2.00×10^{-4}
7θ	Nil

Table IV

HARMONIC COEFFICIENTS (a_n)

θ	Right Side Magnet			Left Side Magnet		Computed	
	rotating	stepped 9"	stepped 24"	rotating	stepped 9"	Biallas	Snowden
2θ	.00238	.00287	.00248	.00517	.00364	-	-
3θ	.00193	.00086	.00560	.00197	.00960	-.00082	.00021
5θ	.00487	.00144	.00320	.00609	.00816	.00209	.00197
7θ	.0206	NM	NM	.01812	.01845	.0201	.01845

Dimension for each a_n are in (inches)$^{-(n-1)}$

(NM = not measured)

Table V

TRACKING TESTS

Power cycle time (sec)	Average residual	b	a	$\dfrac{dB}{dt}\left(\dfrac{G}{sec}\right)$
100	5×10^{-4}	.4079	.0018	444
50	5×10^{-4}	.4091	.0165	888
composite of 33, 42, 50	8×10^{-4}	.4066	.0301	1347, 1110, 888

Table V: The equation fitted is $\triangle\Phi = a + b\Phi$ where $\triangle\Phi = \Phi_A - \Phi_B$ and $\Phi = \Phi_A \simeq \Phi_B$. The composite runs were all superimposed on the recorder and could not be individually resolved by this analysis. The slightly larger average residual reflects the scatter of 3 runs - i.e. the line width.
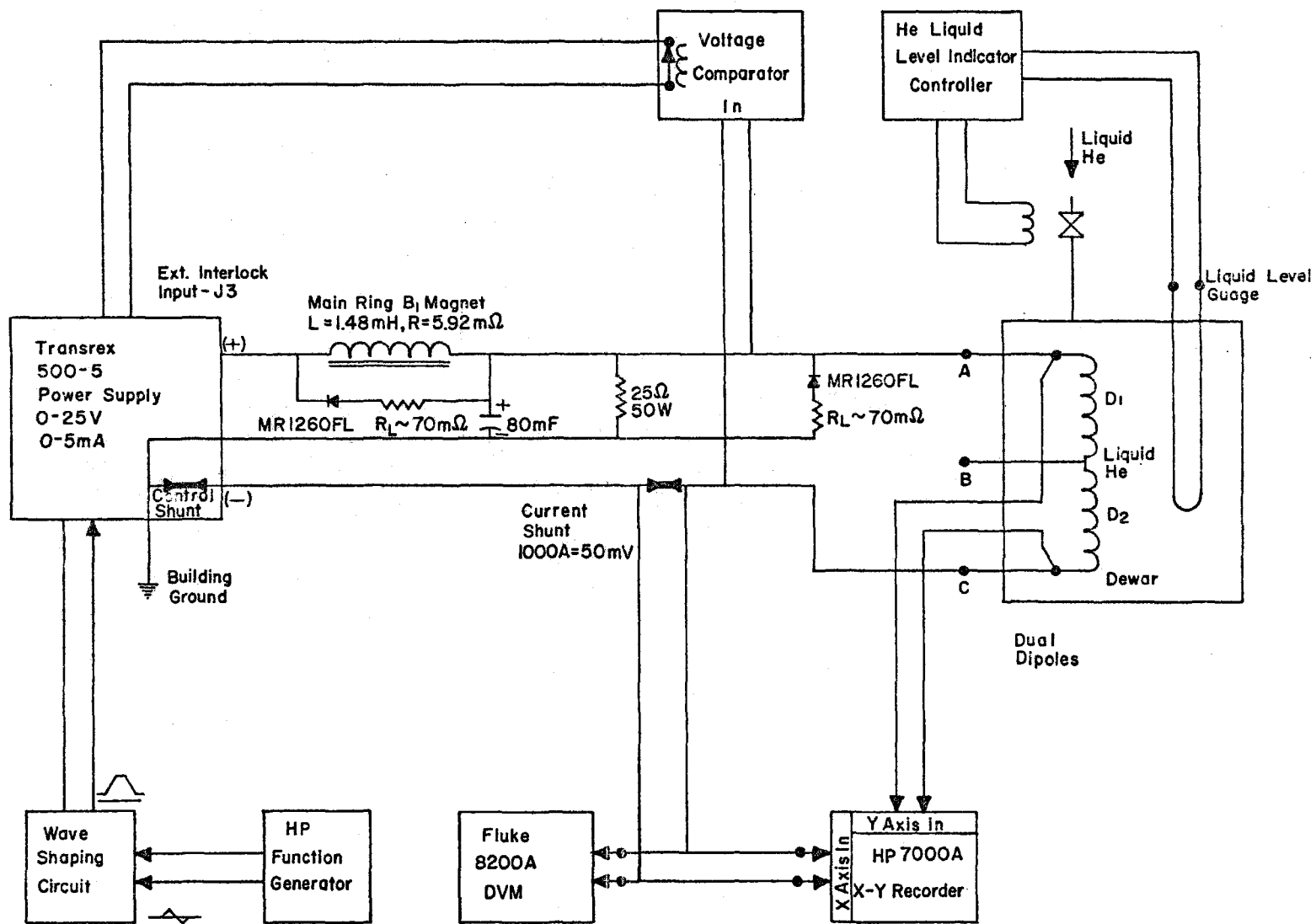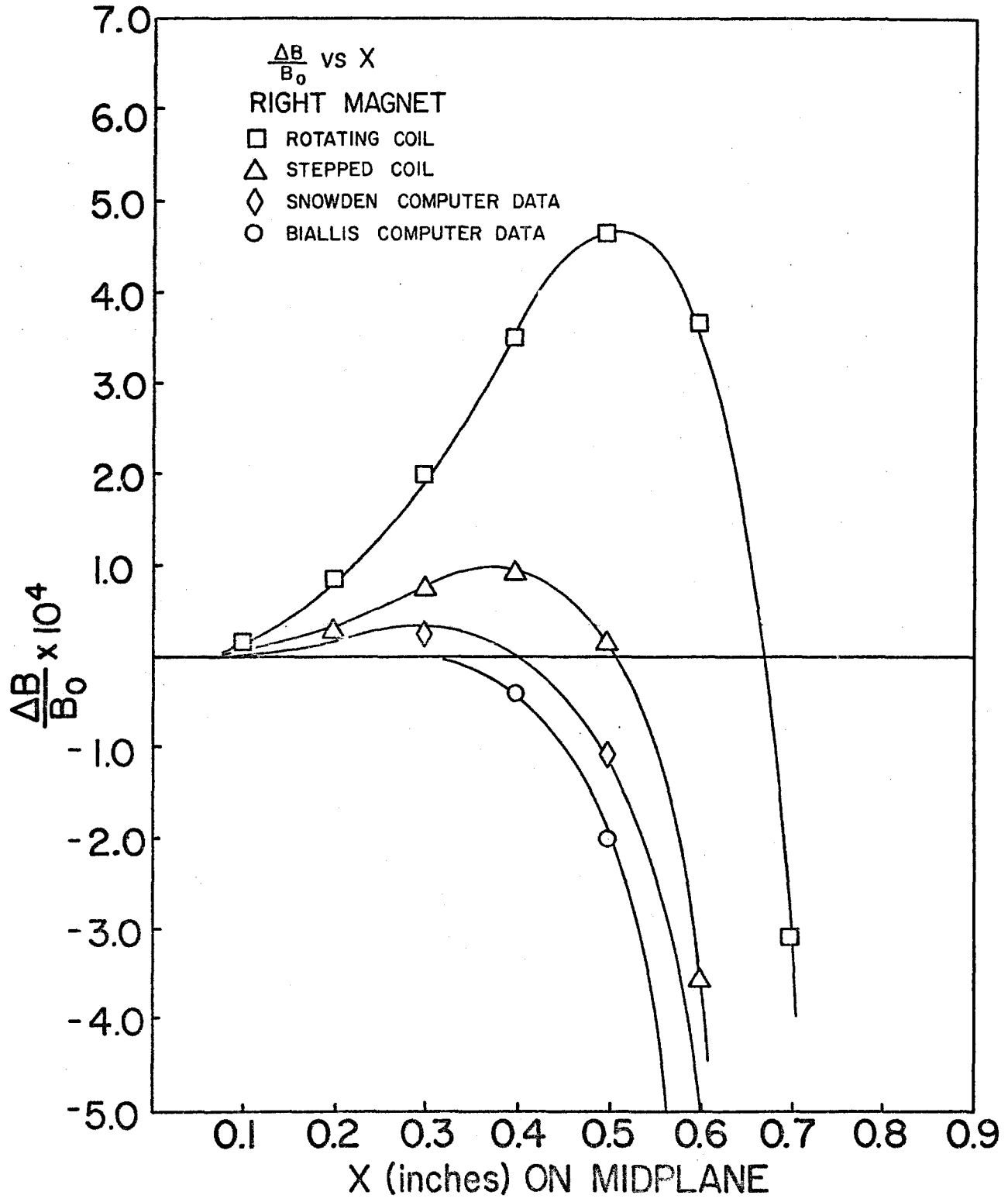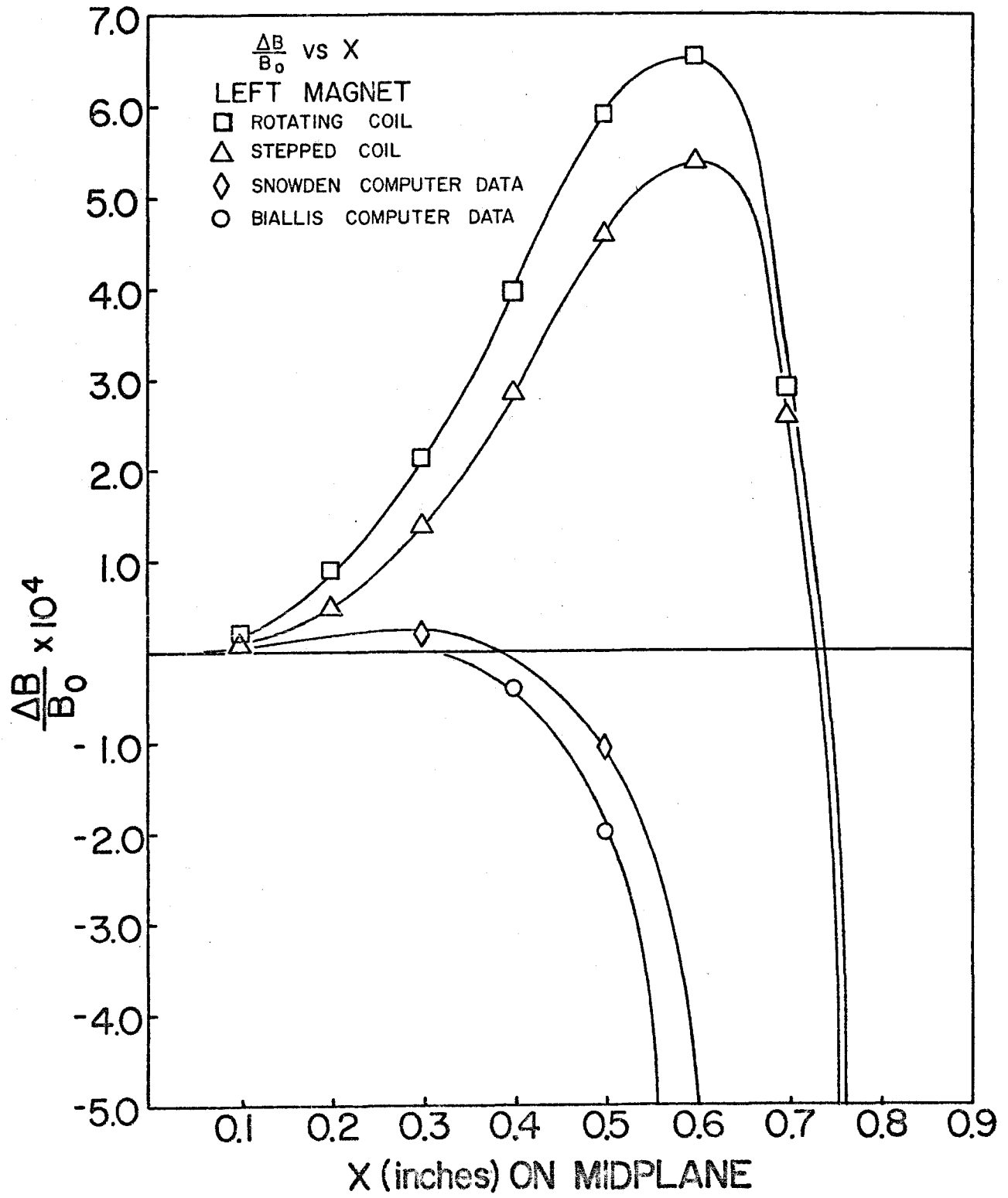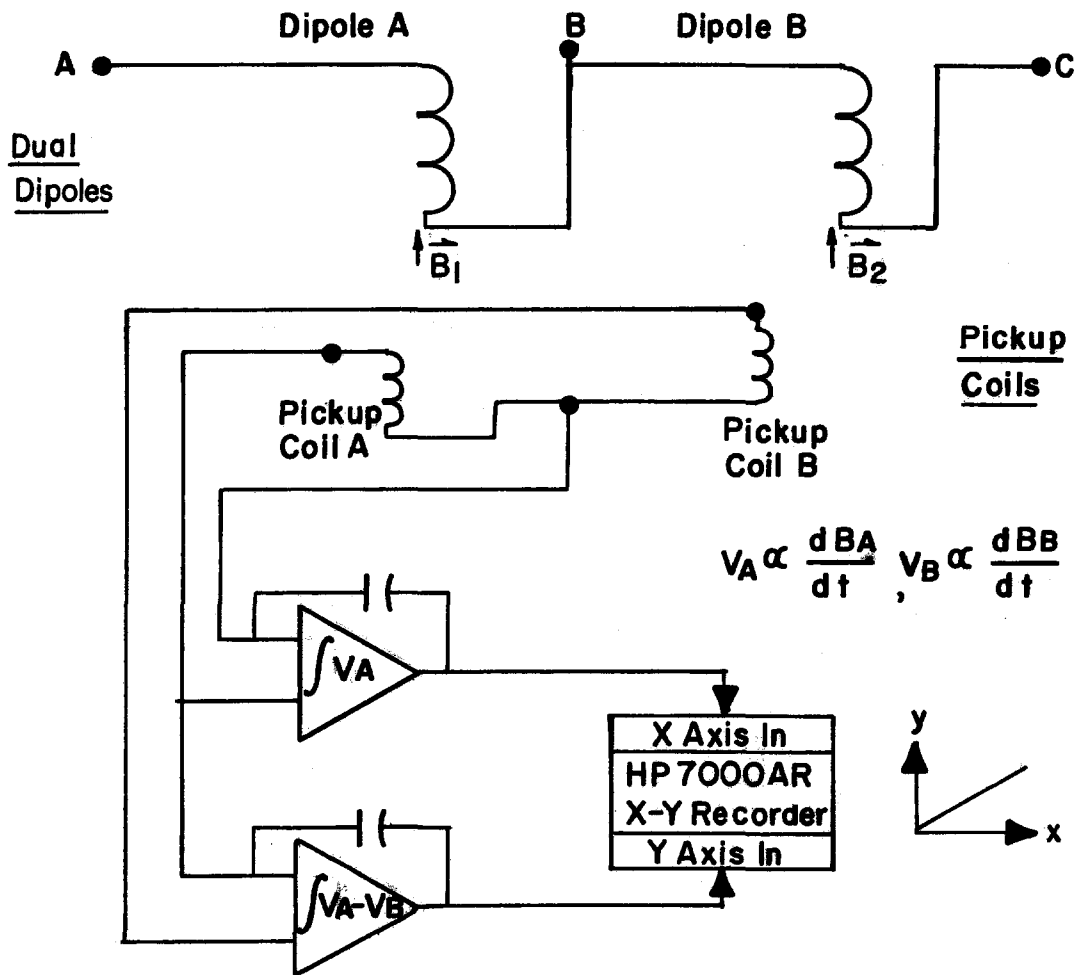
Figure 1

Figure 2

Figure 3

Figure 5
Dual Dipole Tracking Test – Instrumentation