# APPENDIX IX. MAGNET MEASUREMENTS

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## A. Introduction

In the past year, an extensive effort has been made by the Magnet Measurement Group to develop and implement the equipment for the field measurement of Energy-Doubler magnets. An on-line data acquisition system was built for data taking and processing. The ac-loss values of about a dozen magnets were measured by the group. An old D-type 10-ft canned magnet, D10-3, and a new E-type 5-ft canned magnet, E5-1, were tested extensively, using pool-boiling cooling. Their harmonic contents were measured for both dc and pulsed mode, using the newly developed data-acquisition system. The equipment and facility for the production magnet test are installed at the Protomain in the Village.

In addition, methods to measure ac loss and hysteresis loss of superconducting wire were established. A large number of wires were tested for short-sample data and the quality-control testing of production wire is being carried on.

## B. Instrumentation and Facility for Production-Magnet Testing

An advanced data-acquisition system using an on-line mini-computer (PDP-11/10) and a CAMAC system was developed and has been in use successfully for testing superconducting magnets. It can be used to investigate many characteristics, including harmonic analysis of magnetic fields, and we can know exactly and instantly how the superconducting magnet system behaves.

The Protomain, which was used for the original design study of Main-Ring magnets and also for the study of the liquid-helium loop, has been converted to test production magnets. There is a complete set of equipment installed, including a set of magnet stands with end boxes for superconducting magnets, a vacuum system, a control system and a power supply. They will be used for extensive study of prototype magnets and production magnets. For the production testing of all magnets, we need at least two sets of test stands for bending magnets and one set for quadrupoles. Liquid helium from a Gardner refrigerator system with a 1000-gallon dewar will be force-circulated through a 50-ft transfer line and a 200-ft loop

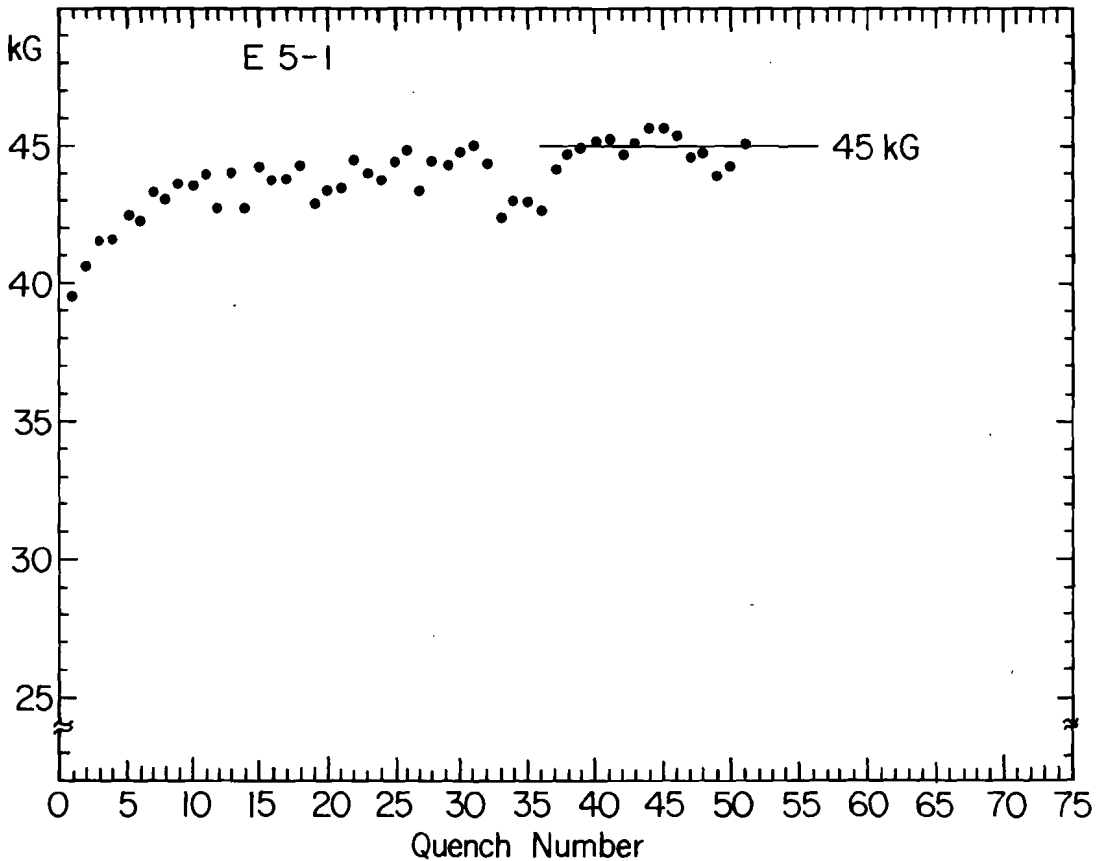



Fig. IX-1. Training curve of E5-1 magnet.

line. The temperature of the liquid helium can be varied downward from the standard 4.7K.

## C. Procedures for Production-Magnet Tests

After a magnet is finally assembled with canning and lamination cores, it will be tested using the equipment and facility above. The following procedure will be used for production tests of a magnet after simple vacuum-leak tests:

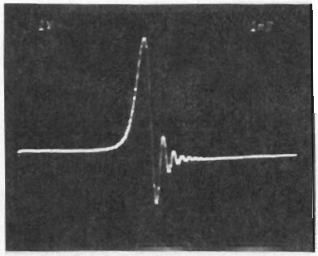
1. The magnet will be trained up to maximum field.
2. Ramp-rate dependence of the magnet will be measured.
3. AC loss of the magnet will be measured.
4. The integrated field value of a bending magnet or the integrated-gradient value of a quadrupole magnet will be measured in pulsed operation from injection field to the maximum field.
5. The magnetic median plane of the magnet will be determined electronically by finding a vertical magnetic symmetry plane, and survey marks will be put on the outside surface.
6. Heat loss of the magnet will be measured.
7. Remanent field and some low fields will be measured.
8. Harmonic analysis of the field distribution will be done for both dc and pulsed operation on some sample magnets.

## D. Prototype Model-Magnet Test

Extensive magnet tests and field measurements were done on the D10-3 and E5-1 magnets.[1] These magnets were canned and provided with lamination cores. They were tested with pool-boiling cooling. The training curve of the E5-1 magnet is shown in Fig. IX-1; its central field value exceeded 45 kG after some training.

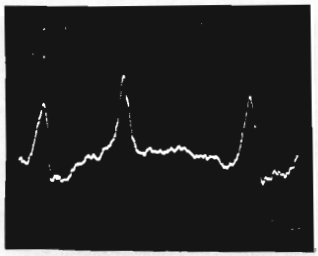
Training curves, ramp-rate dependence, quench behavior and ac loss were measured on these magnets. Field shapes were measured with a Hall-probe gaussmeter for general features. For precision field measurement, a harmonic-analysis method was carried out.

A special method using an NMR circuit and signal averaging was used to measure the absolute field value. The NMR signals obtained are shown in Fig. IX-2. The signal at 20 kG is from protons without signal averaging. The ones at 30 and 44 kG are from $^{7}$Li and obtained with signal averaging. The transfer function is shown in Fig. IX-3, which shows the saturation effect of iron beyond 35 kG. The lamination used for the E5-1 magnet was smaller than the final one, and we should



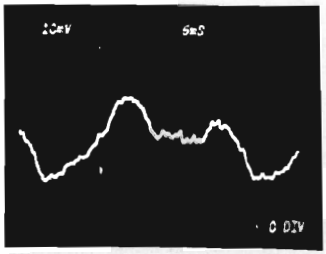
Proton

2000 A (~20 kG)
85.661 MHz
= 20.12 kG



$^{7}$Li

3000 A (~30 kG)
49.953 MHz
= 30.19 kG
After signal averaging




$^{7}$Li

4400 A (~44 kG)
72.954 MHz
44.09 kG
After signal averaging

Fig. IX-2. NMR signals in E5-1.

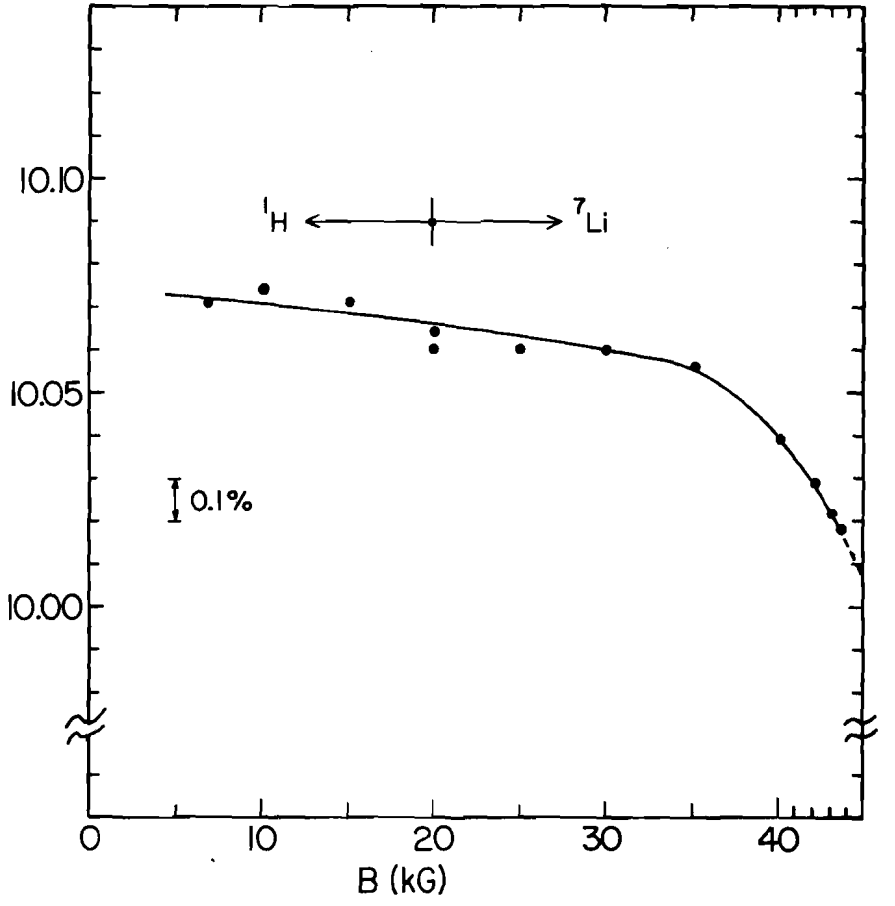



Fig. IX-3. Transfer function using NMR.

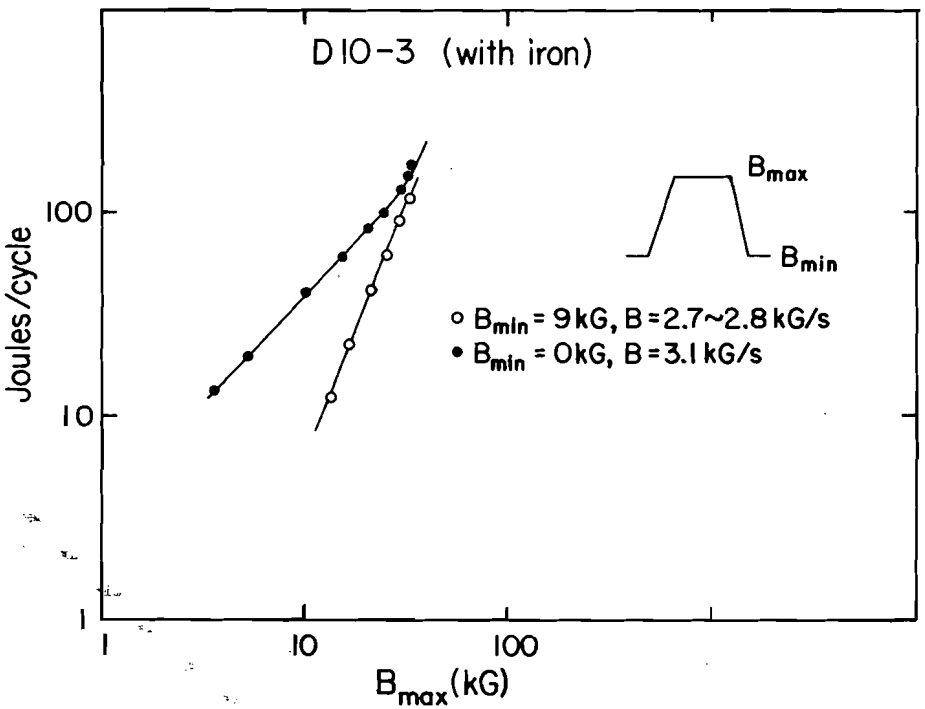



Fig. IX-4. Energy loss, banded magnet.

expect less saturation effect for the final design of the lamination.

## E. AC-Loss Test on Magnets

The total energy used during a cycle can be measured electronically using the on-line data-acquisition system. This is an excellent diagnostic method to test a magnet. If the magnet structure is not adequate for strong magnetic forces at high field, we can infer from this measurement that the wire is moving and causing an excessive extra energy loss. We can also tell whether the superconducting wire is within specification.

A half-dozen 1-ft magnets, one 5-ft magnet, three 10-ft magnets, and one 22-ft magnets have been measured for their ac loss.[2] The ac-loss curves of the D10-3 magnet (banded structure), and E5-1 (collared structure) are shown in Figs. IX-4 and IX-5 respectively. The ac-loss curves of all banded magnets show a bend around 20 or 30 kG, as shown in Fig. IX-4, reflecting a rapid increase in ac loss at higher field. This fact is attributed to wire movement inside a magnet caused by structural deformation under the strong magnetic force. Also shown in Fig. IX-4 is a curve of ac loss for operation starting from 9 kG.

The newly developed collared magnet, E5-1, does not show a high-field bend in its ac loss, as shown in Fig. IX-5. This means that the collared structure is strong enough to hold the wire in place. This implies there is no additional ac loss or extra field distortion caused by wire movement. The circle at 45 kG is the calculated value for a 5-ft magnet from wire data. They are in good agreement. The low-field bend around 3 kG is caused by the penetration of field into the superconducting filaments.

## F. Harmonic Analysis of Magnetic Fields

The on-line data acquisition system was used successfully for harmonic analysis of magnetic field measurement of the D10-3 and E5-1 magnet.[1] It was used for both dc and pulsed-mode operation. The data were taken automatically using Morgan coils. The sextupole component of E5-1 magnet during pulsed-mode operation is shown in Fig. IX-6, which is taken at 0.75 in. radius. It shows a hysteresis curve caused by magnetization of the superconductor. The various measured coefficients of the E5-1 magnet up to octupole are shown in Fig. IX-7, where $b_1$ and $b_2$ are normal quadrupole and sextupole coefficents and $a_1$ and $a_2$ are the corresponding skew coefficients. The measurements were made up to 40 kG. In addition, quadrupole and sextupole terms were measured at the ends.

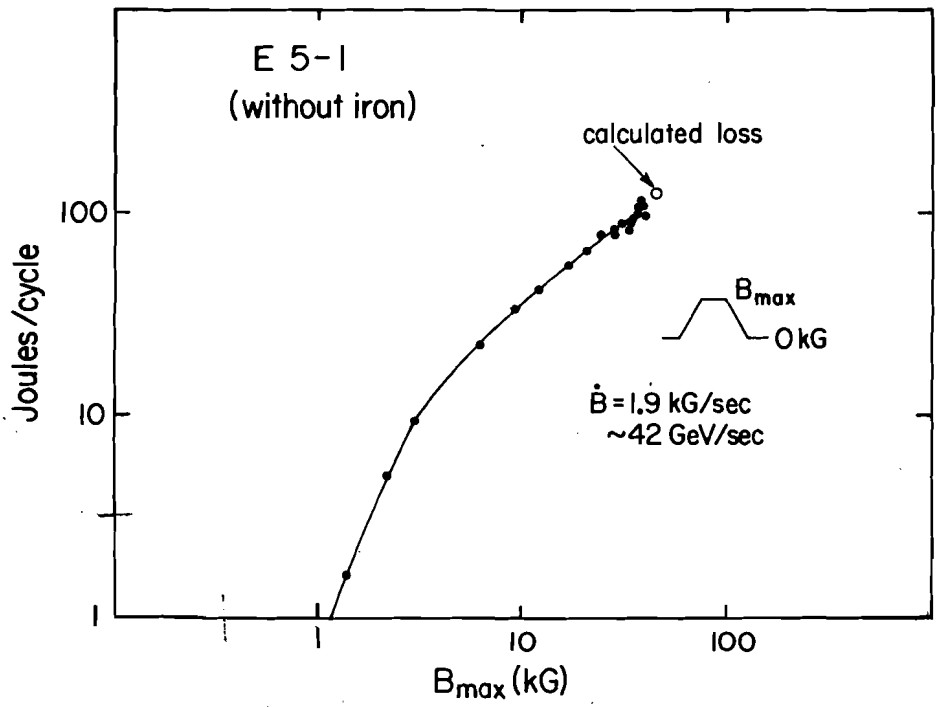



Fig. IX-5. Energy loss, collared magnet.

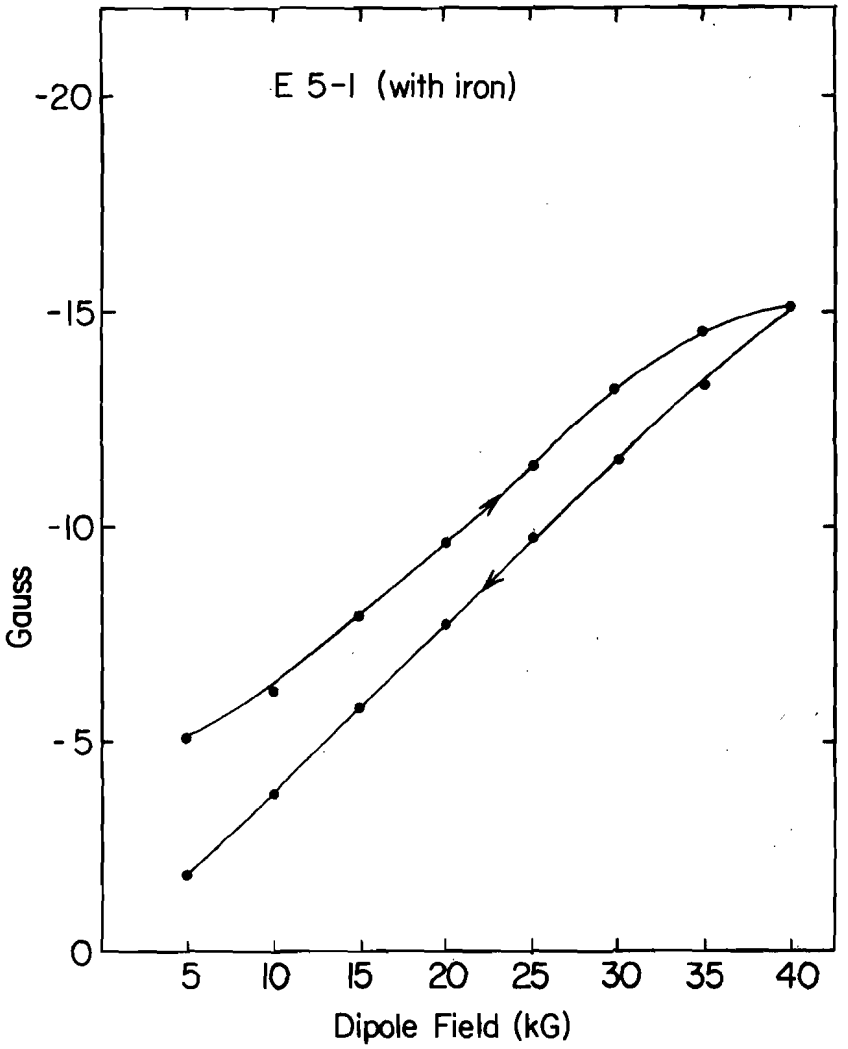



Fig. IX-6. Hysteresis of sextupole field components.

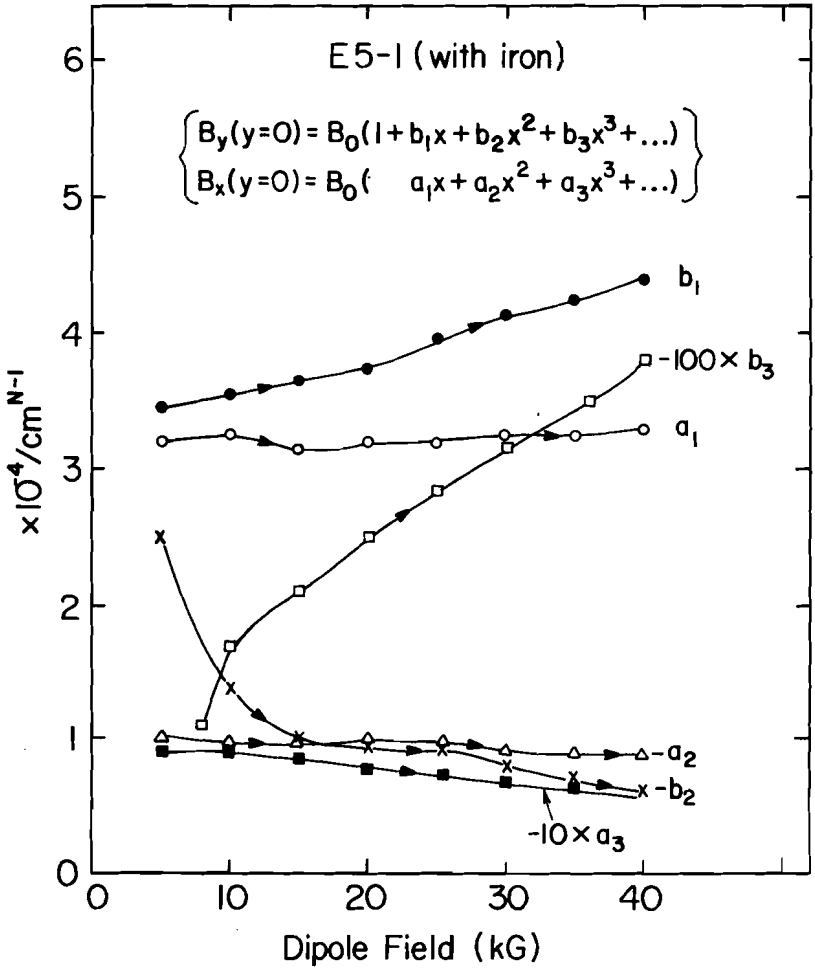



Fig. IX-7. Multiple components of E5-1 magnet.

## G. Superconducting-Wire Tests

The NbTi superconducting cables that are being used for Energy Doubler magnets have been investigated extensively. The ac-loss, hysteresis loss and short-sample data of wire were measured both in the short-sample form and in solenoidal form.[3] These measurement methods were established and permanent equipment is set up. The ac-loss and maximum-field values in real magnets are interpreted in light of thse data from wire samples, which have proven to be essential for the understanding of magnet operation.

The electronic-magnetization method was used to measure the ac-loss of wire.[4] Field-orientation effects on the ac loss was measured for soldered and unsoldered cable. For the perpendicular field, the ac loss of soldered cable strongly depends on ramp rate, because of coupling between strands. For this reason, soldered cable was abandoned. The hysteresis losses of short pieces of cable are measured at very slow ramp rates in three different orientations relative to the magnetic field.[5]

The short-sample data are measured in external fields of 30 to 60 kG for both single-strand wire and cabled wires. Quality control of production wires of single-strand and 23-strand varieties is now routinely being conducted. Resistivity tests of copper are also being done.

References

[1]R. Yamada et al., Operational Test and Field Measurement of D10-3 Magnet, TM-651, 0428.000, March 26, 1976.

[2]R. Yamada et al., AC Loss Test of D10-3 Magnet, TM-638, 1600.000, December 30, 1975.

[3]R. Yamada et al., Superconducting Wire Test at Fermilab, TM-598, 1600.000, July 1975.

[4]H. Ishimoto et al., AC Loss in Flat Transposed Superconducting Cable, TM-636, 1600.000, October 28, 1975.

[5]M. E. Price and R. Yamada, Hysteresis Loss Test of Superconducting Wires, TM-639, 1600.000, December 15, 1975.