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RECENT MEASUREMENT RESULTS OF ENERGY DOUBLER MAGNETS

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ABSTRACT

The methods and results of measurement of more than 100 Energy Doubler magnets are described. Training, quenchbehavior, ac loss, integral field, longitudinal homogeneity DC and AC multipole content, and vertical-plane angle measurements are described.

INTRODUCTION

The evolution of Energy Doubler magnets since the development of a superconducting accelerator at Fermilab began in 1972 has been described in numerous reports to previous accelerator conferences[1] and in other places.[2] Basically, the Energy Doubler is a superconducting synchroton whose magnets will be installed under the existing conventional magnets in the Main Ring tunnel. Injection will be at approximately 100 to 150 GeV from the Main Ring. The Energy Doubler magnets are to be capable fo containing 1-TeV protons at fields of 4.3 T and the ring will also be capable of being operated as a storage ring for both protons and antiprotons made by Main Ring protons, then cooled. The synchrotron will also make possible welcome savings in Fermilab's large power bill and the first phase of the project is to build an Energy Saver ring.

There have been a number of advances in the magnet design since the previous conference, including:

1. a new collar[3] (called "Type V") to hold the coils firmly in place during excitation.
2. use of Ebonol-treated strand (replacing Stay brite) to reduce eddy-current losses during ramping. The losses have been reduced to one-fourth of their previous value.
3. redesign of the pressure-relief system to lower the pressure rise during quenching.
4. reduction of the dipole length from 22 to 21 feet to give more lattice space for correction elements.

There have been significant sucesses in cooling a large (25 magnet) strings of magnets and transporting 90-GeV protons through the string. This work has shown that it is possible to transport beams in a large superconducting system without great difficulties from quenching.

Simultaneously, a magnet test facility has been developed, built, and is in full operation[4]. It is shown in Fig. 1. The facility's 1500 W CTi-Sultzer refrigerator and subcooling distributor is capable of independently cooling magnets on all six test stands (5 dipole and 1 quadrupole). Magnets are cooled in approximately 4 hours and tested at 4.7K in single phase liquid helium. After some minimal training to full field, ac losses, integral field, DC and AC multipole distributions, remanent fields and vertical-plane orientation are measured for each magnet.

A computerized measurement system taking data through a CAMAC PDP-11 configuration is used. The summarized data are transferred and stored in the Fermilab PDP-10 for access by anyone interested in Energy Doubler magnet data.

We have carried out more extensive investigation of effects such as quenching and heat cycling in particular magnets and will describe them later in this report. A system of room-temperature measurements at low fields has been developed by R.E. Peters[7] to give rapid feedback to the production process and the correspondence between these measurements and the superconducting results from our facility has been studied in detail. With appropriate scaling of the dipole and sextupole components to account for the differences arising from the lack of a steel yoke the room-temperature measurements give accurate prediction of superconducting performance.

We now turn to a more detailed discussion of recent results.

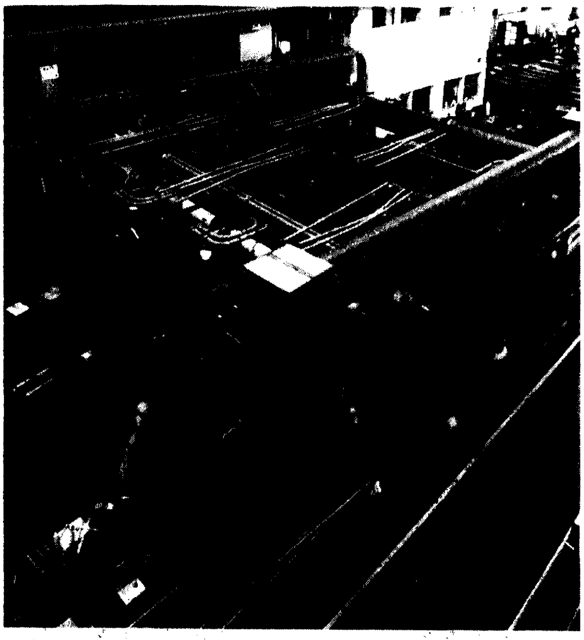

Fig. 1. Magnet Test Facility
Big pipes are exhaust pipes for quenching. Vacuum insulated transfertubes are connecting 6 magnet stands to distribution box.

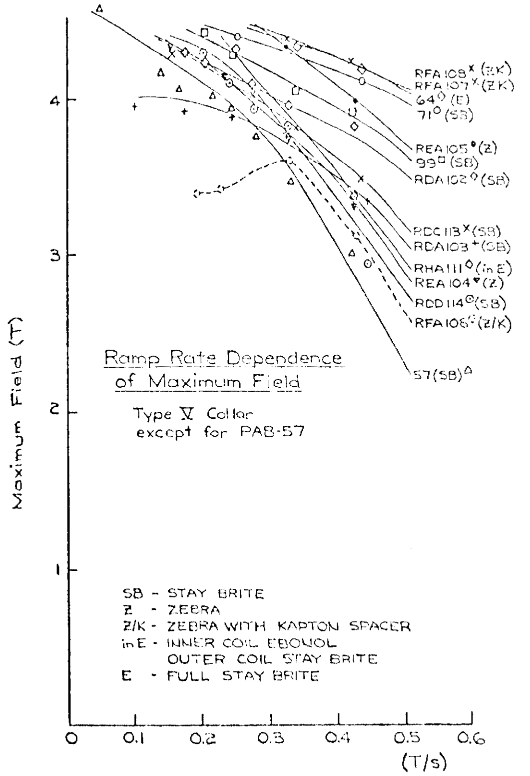

Fig. 2 Ramp Rate Dependence of Quench Current

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DIPOLE MAGNETS

1. Training and Maximum Quench Currents. In these measurements, a quench is detected by monitoring the resistive voltage across the magnet. The inductive voltage drop is bucked out by a toroidal coil coupled to the current bus. When a quench is detected, most of the stored energy is dumped by a thyristor switch into an external water-cooled resistance. At full current, only 0.1 MJ of the full 0.5 MJ stored energy is dissipated in the magnet. We have separately studied dumping the full 0.5 MJ in the magnet as part of the pressure-relief tube redesign mentioned above. We have also measured the field changes with quenching and found them to be very small.

With the tight restraints of the Type V collars, very little training is needed to reach full field. Magnets usually reach 4300A at a 200A/sec ramp rate after a few quenches. Figure 2 shows a typical ramp-rate dependence of maximum quench current.

There have been some recent magnets that could not reach 4300A. The low maximum quench currents were closely correlated with low short-sample currents of the cable used in the coils. A detailed investigation by W.A. Fowler has indicated that the low current capability is traceable to a few bad billets of superconducting strand.

2. AC Loss. Most of the eddy-current loops have been eliminated by the use of Ebonol-treated strand[5]. The ac loss is now consistently smaller than 500 J/cycle, which is low enough to allow operation at 50 GeV/sec rate of rise with the planned refrigeration system.

3. Integral Fields. The integral fields is measured as a function of excitation by a stretched-wire system. The integral field is approximately 6.409 T-m/KA. Figure 3 shows the dependence on excitation and it can be seen that the hysteresis is quite small. The stretched-wire system is a difficult measurement and we have therefore recently developed equipment that scans the field through the magnet with a NMR probe and a NMR-calibrated Hall probe for the fringe fields. This system is providing a more accurate absolute integral field as well as the longitudinal (z) structure of the field. An example is shown in Figure 4.

4. Multipole Fields. The field in the beam bore is measured by a harmonic coil. To give an accurate description of the field, harmonic components up to the 30th pole are required.

Our coil is 8 feet long and therefore three measurements are required to cover an entire magnet. Signals are analyzed in real time and transformed to normal (b_n) and skew (a_n) harmonic components defined as

$$B_y + iB_x = B_o \sum_{n=0}^{\infty} (b_n + ia_n)(x + iy)^n$$

where the pole number is 2 (n+1). The sextupole and decapole values are used to adjust the key angles of the coils. Figure 5 shows the history of sextupole component changes.

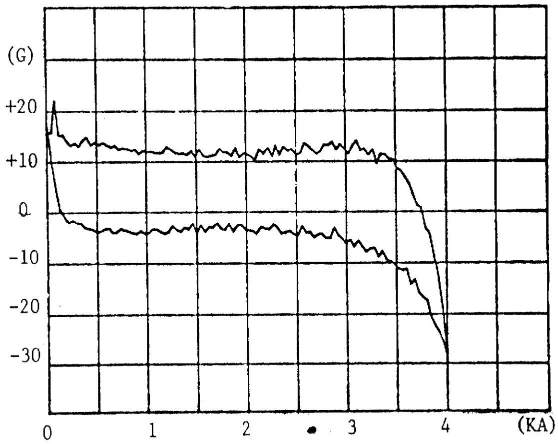
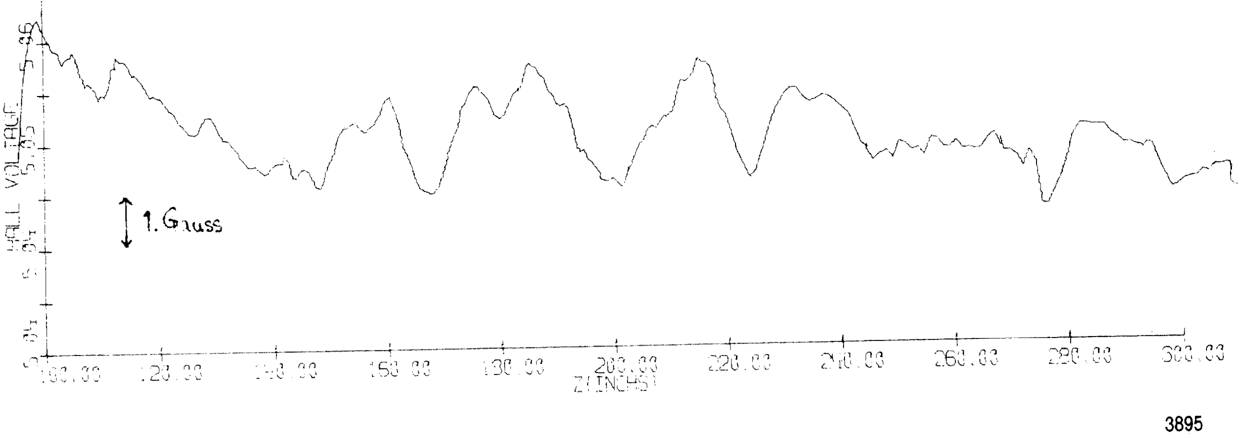


Fig. 3
Field Deviation From Linear Line in PCA-159.
Reference line was taken as B(KG)=9.979I(KA). This data indicates that magnet hysteresis is 14G and saturation of the Iron became visible around 3000 A then reaches up to 20G at 4000A.

POLE	NORMAL	SKEW
2	1	
4	4.542E-6	6.823E-5
6	-4.785E-4	-9.876E-5
8	-9.913E-6	-1.583E-5
10	8.838E-4	-5.766E-5
12	-3.867E-5	-7.819E-5
14	5.296E-4	-9.400E-6
16	-1.326E-4	1.169E-4
18	-1.681E-3	-4.401E-5
20	1.159E-5	1.314E-5
22	5.773E-4	-1.115E-5
24	1.870E-5	-1.566E-5
26	-1.587E-4	7.454E-6
28	-9.009E-8	-9.774E-6
30	1.037E-5	-3.141E-6

Table I
Harmonic component of integral field in magnet PCA-159 at 1.0 inch from the center of the field. The measurements were carried out in three positions to cover whole magnets with 8' long harmonic probe coils. The current is 4000A. (40KG)

Fig4 HALL PROBE SCANNING



There have been some difficulties with overpressures in the collaring process partially crushing the small helium irrigation channels located next to the inner-coil keys. The resulting changes in coil dimensions are mirrored in changes in the sextupole. With careful attention to quality control, it is now feasible to build production magnets whose multipole components are all within tight tolerances.

Because of persistent currents in superconductors, some multipole components have large hysteresis effects, as shown in Figure 5, but they are quite reproducible. They are, of course, less important at higher excitations. There are no observable saturation effects on the multipole components, because the iron is far from the coils. Figure 7 shows the vertical field profile in the median plane.

Harmonic components are also measured dynamically with ramping current. Figure 8 is a comparison between AC and DC. As predicted for reduced eddy-current loops, very little effect of the ramp rate is observed in Ebonol magnets.

5. Field Orientation. The cryostat is aligned with the magnet yoke at room temperature during assembly by nulling the field through a wire loop in the yoke oriented in a vertical plane. The vertical plane is then measured in the superconducting state by a stretched-wire technique.

The magnitude of the deviation of magnetic from yoke vertical has been of concern to us, because it has large consequences on the sizes planned for correction dipoles. Results are discussed in the statistical section below. We are still refining our techniques in this measurement.

QUADRUPOLES

At the time in 1978 when the early prototype quadrupoles used in the 25-magnet string mentioned in the introduction were to be measured, our quadrupole stand was not complete and those five quadrupoles were measured in pairs on a dipole stand. We have since completed the qudrupole stand and have been developing measurement techniques on the first new-series quadrupole (QB2) manufactured.

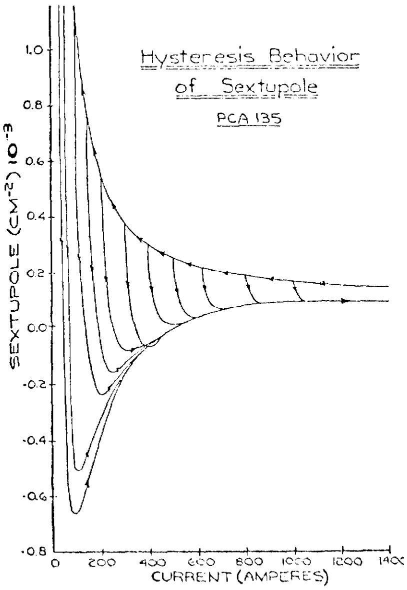


Fig. 6 Hysteresis Behavior of Sextupole
Data was taken from various minimum currents to see the change in the hysteresis loops.

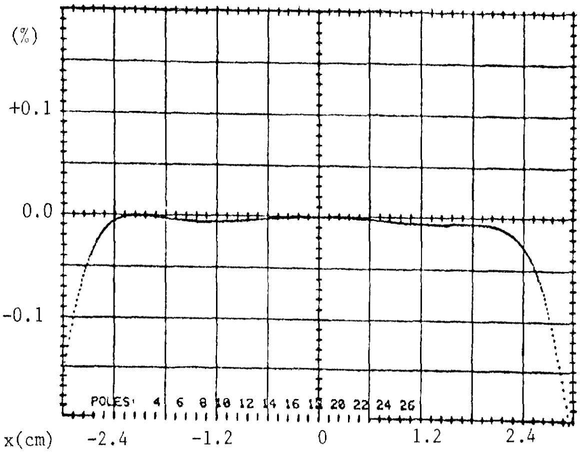


Fig. 7 Field Deviation of PCA-159 in the X-Plane. The field is reconstructed from harmonic components taken at 4000A.

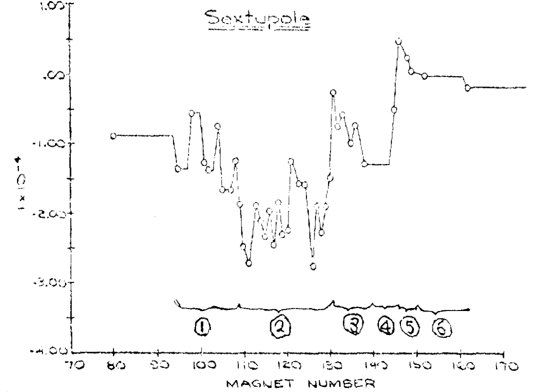


Fig. 5 History of Sextupole Control
Making measurement data as a negative feedback for the shimming angle, it is possible to control the field homogeneity. Increased compaction made sextupoles larger (1-2) then shim angles were adjusted to make it smaller(3). Over accidental collasping of the irrigation channels (4-5) shims were readjusted and the sextupoles settled down very close to the designed values. (6)

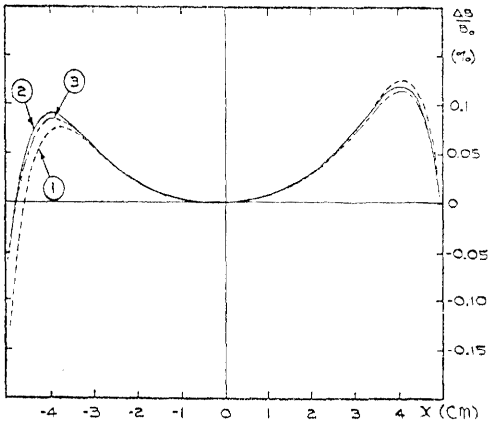


Fig. 8 Field Profile of PCA-148 in Different Ramp Rates at 4000A.
4,6,8,10,18, pole components are used to reconstruct the field. The ramp rates are (1) DC (2) 160A/sec (3) 270A/sec. This data includes only body field. Positive sextupoles are to be cancelled by negative sextupoles in the end field.

1. Quench Current. Maximum quench currents are large (4.57kA at a ramp rate of 670A/sec on QB2) and one can only make the magnet quench at the maximum ramp rate of our power supply.

2. Integral Gradient. The integral quadrupole strength is measured with twin wire loops stretched through the magnet. The relative difference in area of the two loops is approximately 2×10^{-3}. The integral gradient strength in QB2 is 121.6T, whereas the design value is 119.6T Measurement data on more quadrupoles are needed.

3. Multipole Fields. The harmonic coil is composed of two main coils and four supplementary bucking coils. A dipole component arises from off-center positioning of the harmonic coil and this dipole component, as well as the quadrupole component, must be suppressed to give workable sensitivity for higher multipoles. Rough reductions of the dipole and quadrupole are done by the two main coils and further reduction to the order of 10^{-4} is achieved with two orthogonal dipole and two orthogonal quadrupole bucking coils.

The harmonic components are given in Table II at 4000A. The deviation from a pure quadrupole field is shown in Figure 9. The normal sextupole component can be seen to dominate. There are also skew 8 and 10 poles and a normal 20-pole. The excitation dependences of the 12th decapole are shown in Figure 10. The center line of the hysteresis has become much flatter than in older data. This means that the new collars have almost completely eliminated coil motion[6]. The 12 pole is also measured with a Morgan coil and the two methods give similar results.

POLE	NORMAL	SKEW
6	6.32	6.00
8	-0.44	-1.70
10	0.54	-1.82
12	-0.95	0.84
14	0.88	0.31
16	0.01	0.00
18	0.51	0.59
20	-1.63	0.26
22	0.10	-0.03
24	-0.04	-0.11
26	-0.38	-0.50
28	0.60	-0.06
30	0.11	0.79

Table II
Harmonic components of quad integral field relative to normal 4-pole $\times10^{-4}/\text{in}^{1-13}$ in magnet QB-2.

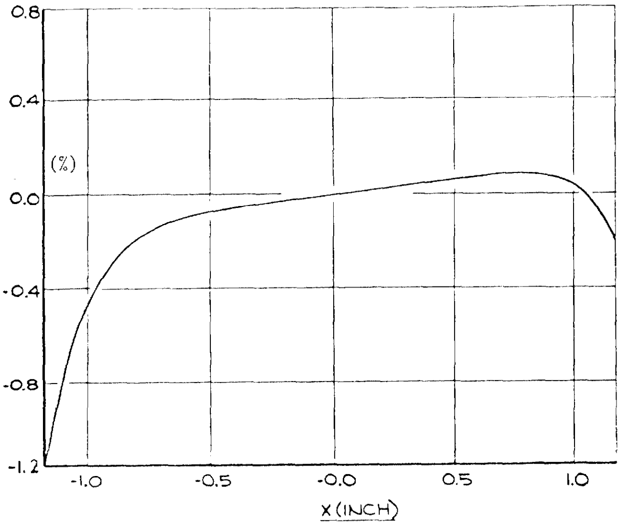


Fig. 9 Gradient Distribution Normalized at the Center

STATISTICAL ANALYSIS OF DOUBLER MAGNET DATA

We have made 100 individual measurements on about 70 Doubler magnets. A statistical overview of the data is persented here.

Figure 11 is a histogram of quench currents at roughly similar conditions, both internally in measurements and with respect to the Doubler operation. The typical temperature in single phase (1Ø) is 4.7K (±0.1K) and 4.55K in two-phase return. Generally the subcooling of 1Ø is 3 psi and mass flow is 20-30 gm/sec.

Recent magnets have been typically made with Ebonol inner coil and Staybrite outer coils and consequently the quench current at 200 A/s-Doubler ramp rate is enhanced. We have also measured the quench behavior of magnets whose coils are made with Zebra conductor and also some with Kapton tape insulator between strands.

Data on a ac loss measurements are summarized in Fig. 12 . Clearly, different types of wire are distinguishable, Staybrite being generally worst (due to eddy-current coupling) and wire containing only Ebonol being best. There is a large reduction in cyclic loss when Ebonol strand is used.

There have been noticeable changes in transfer ratios (Gauss/Amp) with various collaring schemes, as shown in Figure 13 . The FWHM is approximately 0.1% over all magnets measured, however bunching at a smaller width can be percieved as a function of magnet number(which is roughly time). We measure the transfer ratio (TR) by means of a NMR control circuit. Any errors in collaring can be clearly seen and feedback for monitoring and for improving collaring is thus provided.

The integral field is quite hard to measure in a 22-ft. dipole by the stretched wire and until recently some data were inadequate. Nevertheless, at 0.1%, the Doubler magnets are clearly reproducible in effective length. Is shown in Figure 14.

We have made detailed studies of the rotation of the dipole field with quench history and also with (and this is a more violent change) warmup-cooldown cycles. So far we have indications that the field orientation rotates randomly over a heat cycle, but it is within the order of ±0.2 mrad at its maximum. Harmonic components were also measured, but the changes observed were very small.

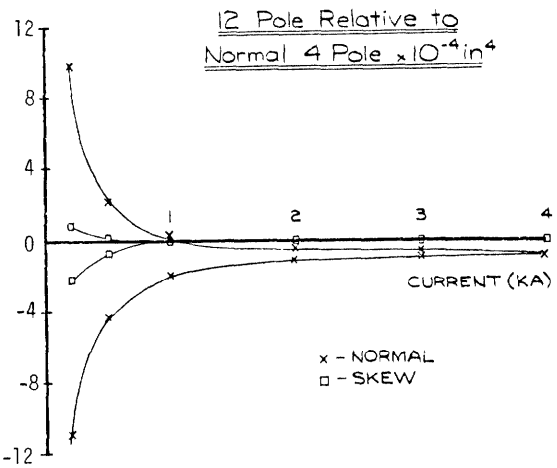


Fig. 10 Excitation Dependence of the 12-pole.

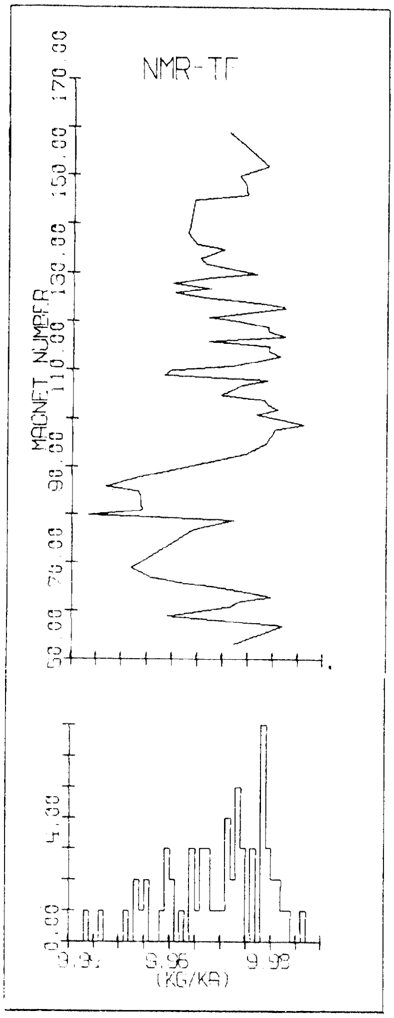


Fig. 13 Transfer Ratio Measured By NMR

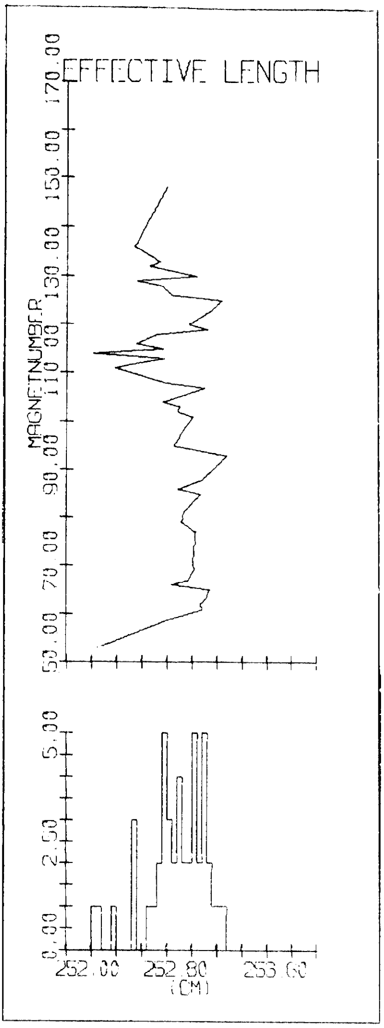


Fig. 14 Effective Length Measured By Stretched Wire.

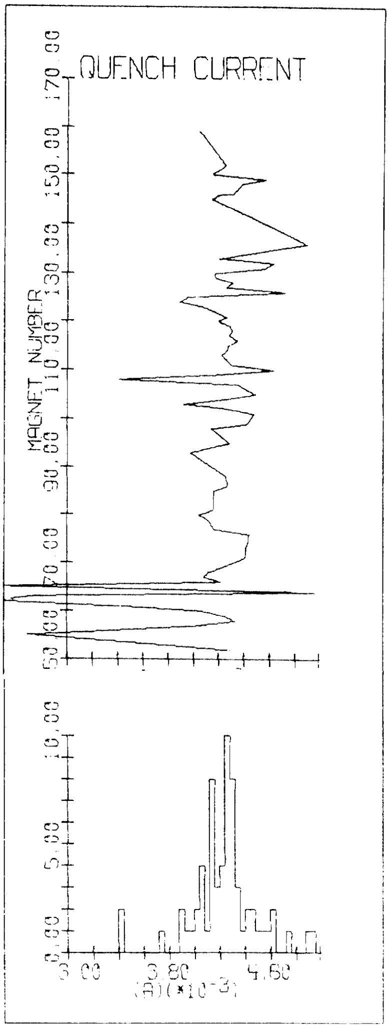


Fig. 11 Quench Current at 200A/sec Ramp Rate

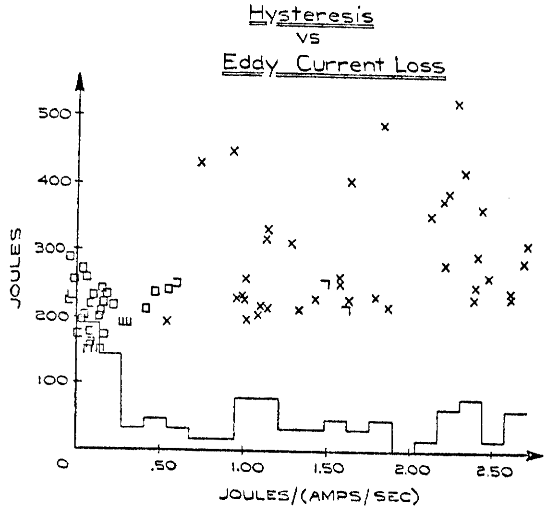


Fig. 12 AC Loss with Various Conductors

x Staybrite
L Ebonol
U Zebra
⊏ Ebonol/Kapton
□ Inner Coil Ebonol
⊐ Inner Coil Zebra
⊓ Zebra/Kapton
˥ Bismuth

CONCLUSION

The Magnet Test Facility has made it possible to carry out a wide series of magnetic measurements on Energy Doubler magnets. The results are quite accurate; fields are measured to the order of 1G in $4x10^4$G, in covering many effects important in the design of the magnets. We believe that the basic principles of the magnet design have been established and that we are now fine-tuning the magnet design to provide fields precise and reproducible enough for all the applications envisaged for the Energy Doubler.

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