TS-SSC 91-226

BIPOLAR AND UNIPOLAR TESTS OF 1.5m MODEL SSC COLLIDER DIPOLES AT FERMILAB

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1 July 1991

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INTRODUCTION

The objectives of these studies were twofold :

- To study the AC losses of SSC model dipole magnets, under unipolar and bipolar ramp conditions, and....

- To measure the magnetic field harmonics, especially B_2, under unipolar and bipolar ramp conditions.

The motivation ?

- The AC losses are an important design consideration for the SSC HEB (High Energy Booster), since the booster will be ramped in a bipolar AC fashion through many cycles as protons and anti-protons are injected into the main ring. These losses will add measurably to the steady-state refrigeraton requirements of the HEB.

Though the HEB magnets are not the same as the main ring SSC dipoles, they are similar enough that the data would be useful. Also, the measurement technique could be evaluated.

- The normal sextupole (B_2) affects the chromaticity and the tune-shift of the beam during injection - both of which deplete tune-space, and can lead to greater beam loss and emmitance.

Therefore, since B_2 must be known and carefully controlled so that the booster can be operated in the most efficient manner, it was important to measure it under bipolar operating conditions similar to those being considered for the SSC.

First - a short (brief, simple!) tutorial on AC losses...

There are 4 primary mechanisms that produce AC losses :

1.) **Superconductor Hysteresis** (Magnetization)

2.) **Eddy Currents** in the Cu matrix of the cable

3.) **Hysteresis** in the iron yoke

4.) **Eddy currents** in other components of the magnet (Cu wedges, collar laminations, etc.)

Eddy Current Mechanisms :

Mechanisms 2,3, and 4 are "normal" - i.e., they are treated in most texts on E&M, and the fundamental explanation for 2 and 4 is basically that of :

Faraday's law of Induction :

$$\oint \vec{E} \cdot d\hat{l} = -d\Phi/dt = -d/dt \int_S \vec{B} \cdot d\vec{A} = V$$

This induced voltage leads to currents, called "eddy" currents, in the conductive components of the magnet that are linked by the change in flux as the field is ramped up/down.

Just like any other current flowing in a resistive medium, eddy currents dissipate energy (heat) through Joule heating :

$V_{CKT} \Rightarrow \underline{I} \longrightarrow \underline{I}^2 R$ Loss...

The power dissipation can be written as :
(Lamm, Haddock)

$P = \sigma \dot{B}^2$ (geometrical factors)

where σ is the conductivity of the conductor carrying the eddy currents

$\dot{B}$ is the rate of change of the magnetic field

and the geometric factors describe the mutual inductance (flux linkage) between field producing conductors and various magnet components.

The dissipated energy is simply the power integrated with respect to time over a closed cycle .

$$\Delta E = \int \frac{dE}{dt}\, dt = \int P\, dt$$

$$\approx \sigma \dot{B}^2 (\text{GEOM FACT}) \cdot \Delta t_{cycle} \qquad \Delta t = \frac{\Delta B}{\dot{B}}$$

FOR UNIFORM RAMP

$$\Rightarrow \quad \Delta E \approx \sigma \dot{B} \Delta B \times (\text{GEOM FACT})$$

Iron Magnetization :

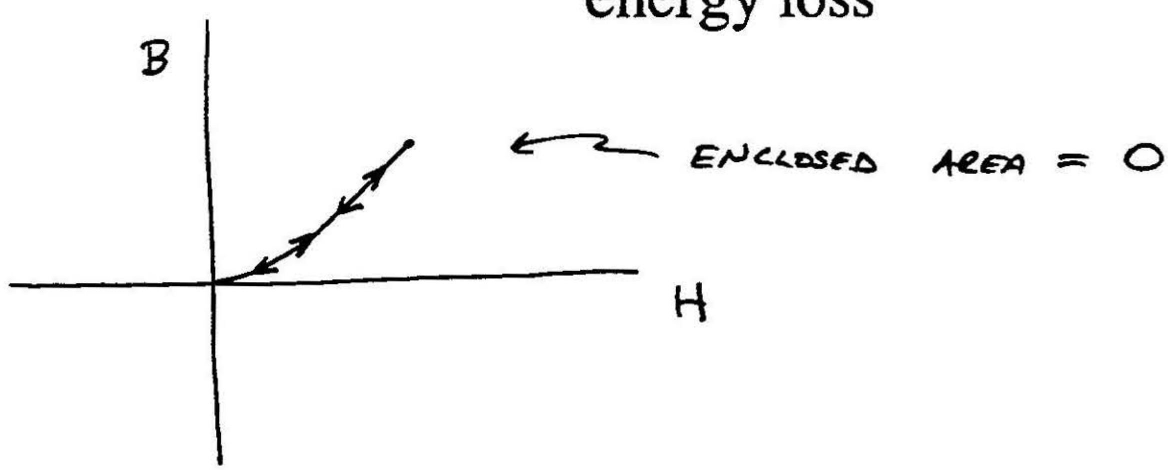
The other "normal" energy loss mechanism (3) is the magnetization loss, or hysteresis loss, in the iron yoke...

The energy dissipated per unit volume over a closed cycle through iron hysteresis is given by:

$$w = \int \vec{H} \cdot d\vec{B} \qquad \text{with } \vec{H} = \text{applied field and } \vec{B} = \text{magnetic induction}$$

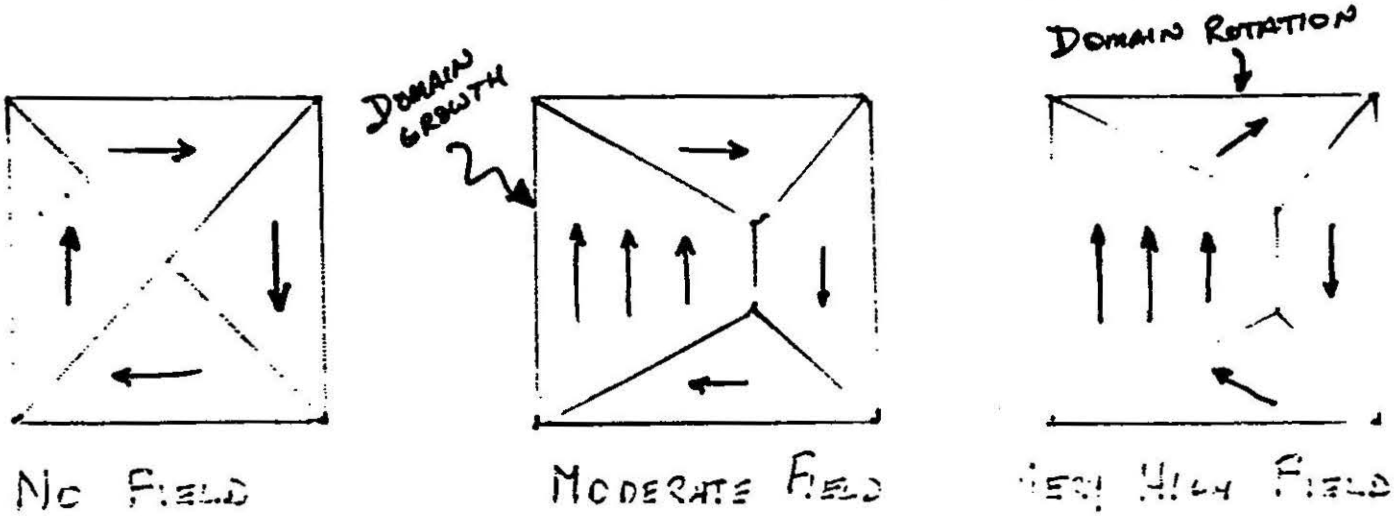
This energy dissipation arises from the re-ordering of magnetic domains (regions of aligned spin) - domains with spin oriented in the favored direction will grow, while oppositely oriented domains will decrease in size.

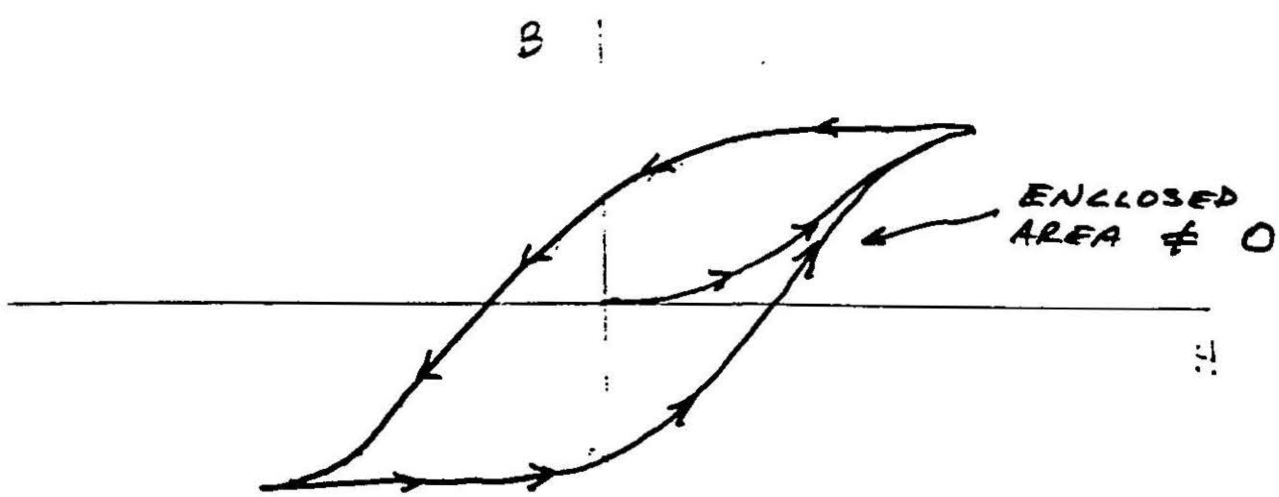
Low applied field : Reversible process, no energy loss



High field : Irreversible process - motion of domain walls may be hindered by crystal defects or impurities: energy barrier to be overcome in increasing domain size, and in returning to un-magnetized state.

Also - at very high field, domain rotation takes place - domain structure difficult to re-form.



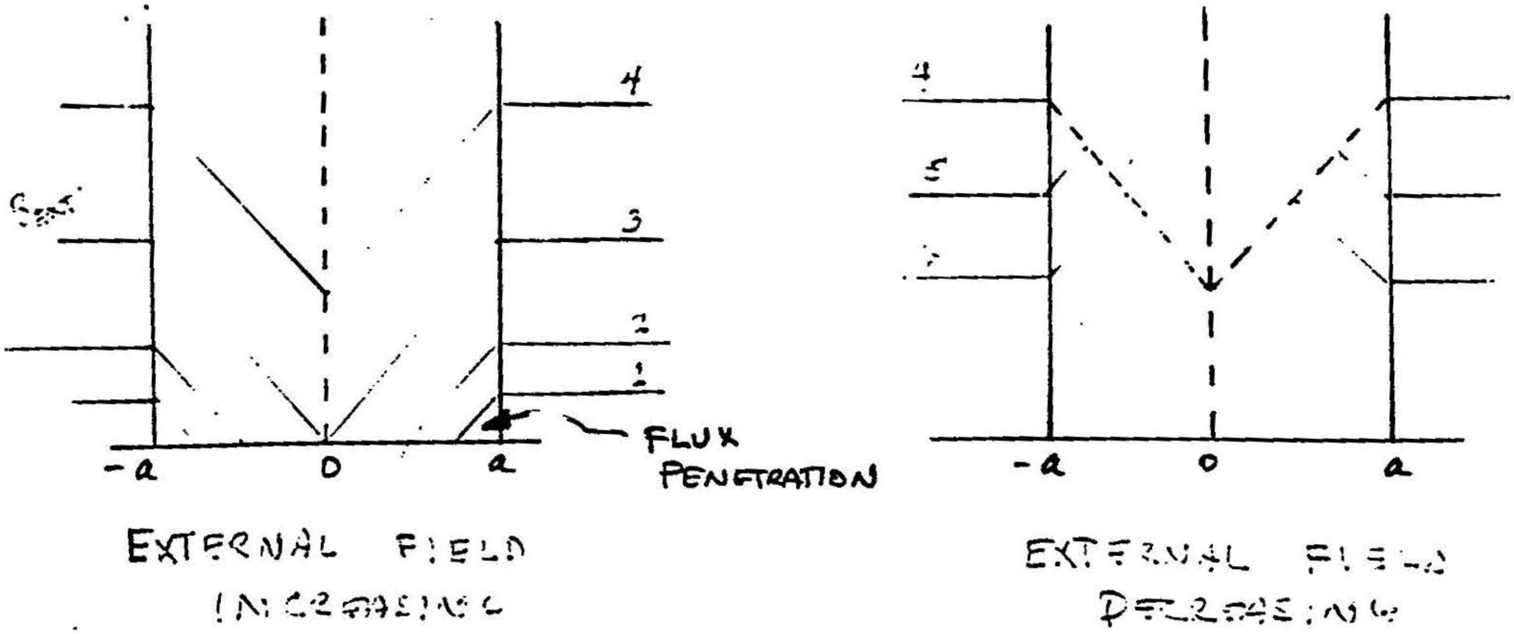


Superconductor Hysteresis :

Recall the Critical-State model :

Screening currents flow in a superconductor, at the critical current density J_c, in order to exclude the external field. The current density does not change in response to changes in the external field - only the current density distribution changes !

One-dimensional model :

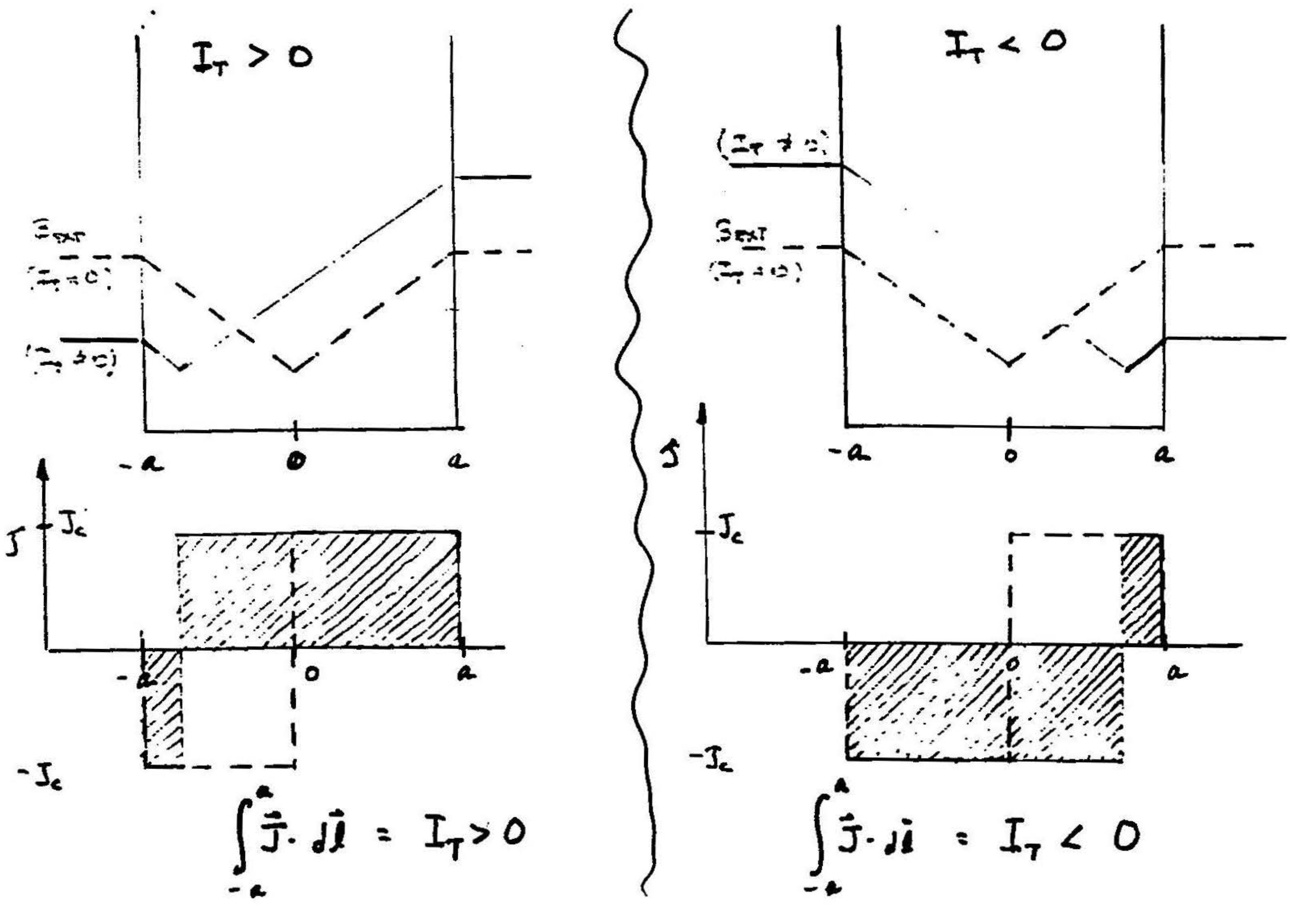


(for $H > H_{c_1}$ = pt. where flux begins to penetrate conductor

Changes in the external field produce flux motion - leaving the lattice in an excited state.

Effect of changing transport current:

Changes in the transport current flowing in a superconductor lead to additional losses called self-field losses. They are due to the added flux motion from the changing field produced by changes in the transport current flowing in the conductor itself. The re-distribution of screening currents (or superconducting eddy currents), in response to changes in transport current, involve flux motion - which again dissipates energy.



The situation is further complicated by coupling between filaments in a strand, and between strands in a cable :

- Coupling between filaments affects the screening current distribution

- Eddy currents flow in the resistive (Cu) matrix of strands, adding to losses

In general, the losses are difficult to calculate, due to the various interactions between the loss mechanisms, and the components of the magnet.

Summarizing :

Cable : SC Hysteresis loss
Filamentary coupling
Eddy currents in Cu

Laminations : Eddy currents in collar and yoke
Magnetization (hysteresis) in iron yoke

Cu wedges : Eddy currents

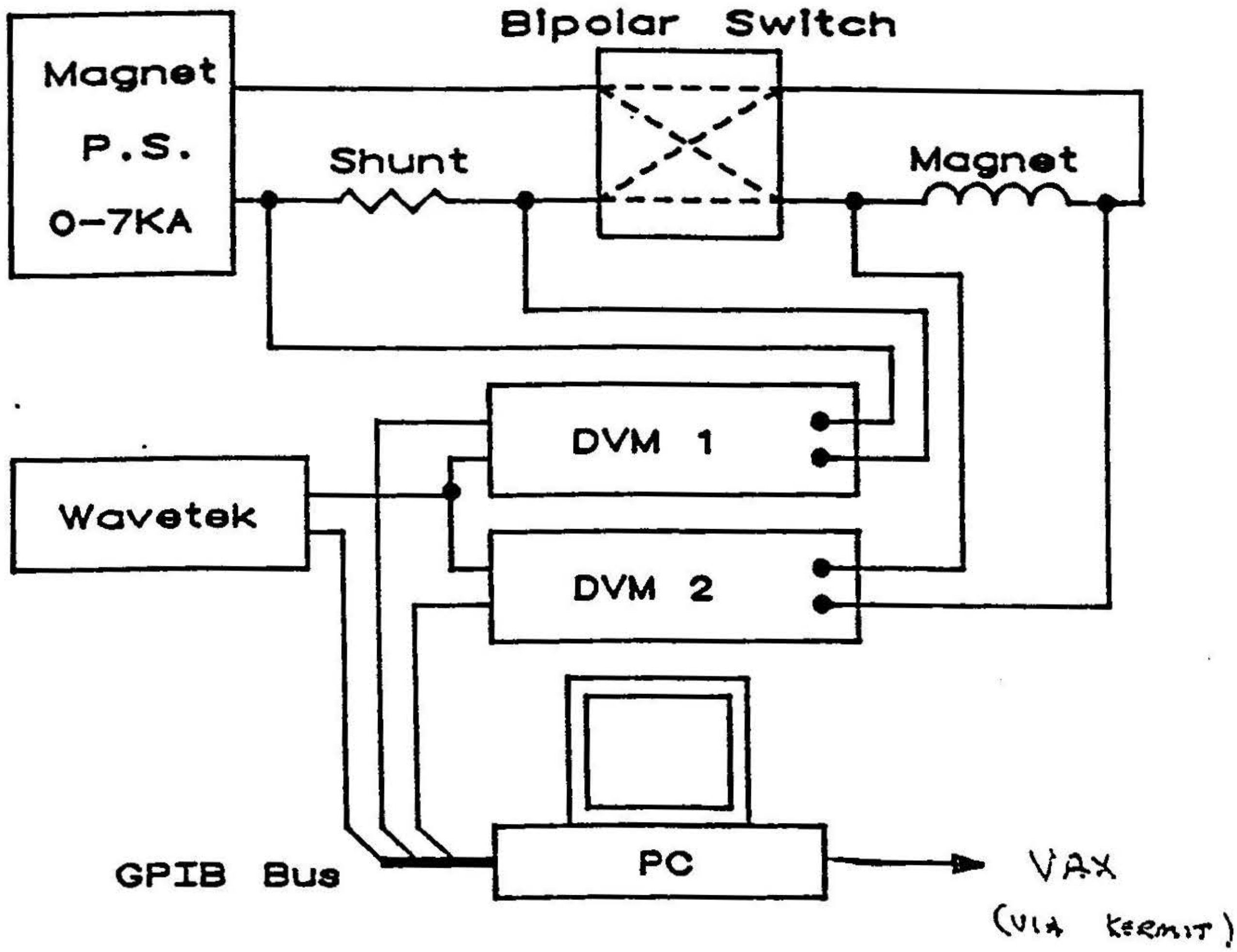
AC LOSS MEASUREMENTS ---

MEASUREMENT TECHNIQUE :

- USE SENSITIVE DVM's TO SIMULTANEOUSLY MEASURE V_{MAG} AND I_{MAG}
- DIGITALLY INTEGRATE (V*I)dt OVER A CLOSED CURRENT CYCLE
- TRIGGER VOLTMETERS SIMULTANEOUSLY USING EXTERNAL TRIGGERING; SUPPLY TRIGGER PULSES USING A DIGITAL WAVEFORM GENERATOR

ADVANTAGES :

- DRIFT OF ANALOG INTEGRATOR ELIMINATED
- USE OF "BUCKING COIL" TO BALANCE OUT THE INDUCTIVE COMPONENT OF V_{MAG} NC LONGER NEEDED --- A TIME-CONSUMING AND CRITICAL OPERATION
- SIMPLER MEASUREMENT SYSTEM; FEWER COMPONENTS


Bipolar Switch
Magnet
P.S.
0-7KA
Shunt
Magnet
DVM 1
Wavetek
DVM 2
GPIB Bus
PC
VAX
(VIA KERMIT)

FIRST MEASUREMENT EFFORTS (MAGNET DSA321)

GOALS :

- BASIC EVALUATION OF THE MEASUREMENT METHOD
- ONE POWER SUPPLY VS. 2 POWER SUPPLY OPERATION
- INPUT FILTER FREQUENCY (4, 100, 1000 Hz) EVALUATION
- 2 DIFFERENT DATA ACQUISITION RATES AND 2 DIFFERENT INTEGRATION TIMES (4.5, 14 Hz; .016, .167 s)
- PERFORM SOME MEASUREMENTS AT DC CURRENT, AND WITH P.S. OFF, TO DETERMINE ANY OFFSET

RESULTS :

- OPERATION WITH SINGLE POWER SUPPLY BETTER; DUAL POWER SUPPLY OPERATION EXHIBITS "GLITCH" IN $I = f(t)$, WHICH LEADS TO A LARGE SPIKE IN V_{MAG}
- 4 AND 100 Hz FILTERS ARE BETTER, AS WAS AN INTEGRATION TIME OF 10 PLC's (0.167 s)
- NO NOTICEABLE ENERGY LOSS @ DC

SECOND MEASUREMENT EFFORTS (MAGNET DS0315)

GOALS :

- MEASURE ENERGY LOSS FOR TWO DIFFERENT RAMP RATES : 100 A/S AND 300 A/S
- AGAIN LOOK AT 2 DIFFERENT INTEGRATION TIMES (0.016 and 0.167 s)
- AGAIN STUDY EFFECTS OF DIFFERENT DATA ACQUISITION RATES (4.5, 15, AND 38 Hz)
- PERFORM MEASUREMENTS WITH AND WITHOUT THE INDUCTIVE COMPONENT OF V_{MAG} SUBTRACTED OUT BY USING THE "BUCKING" COIL FOR CERTAIN RUNS

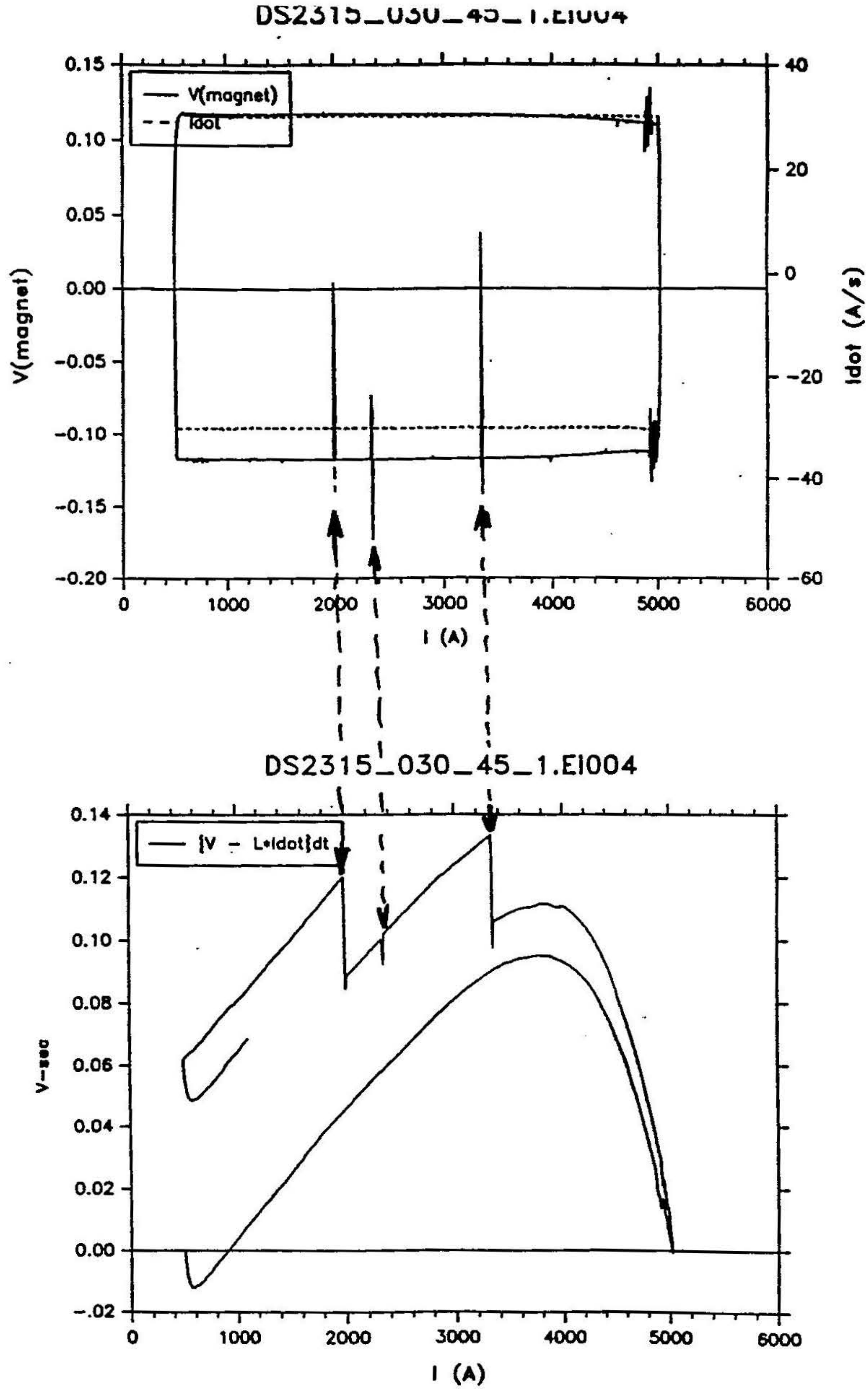
RUN PARAMETERS :

- MODIFIED SAWTOOTH RAMP FROM 500 - 5000 - 500 A 5 SECOND DWELLS AT I_{MIN} AND I_{MAX} TO FACILITATE DATA ANALYSIS
- 100 Hz FILTER USED ON INPUTS, ONE POWER SUPPLY ONLY
- WAIT 3 COMPLETE CYCLES BEFORE TAKING DATA, SO THAT PREVIOUS MAGNETIZATION EFFECTS ARE ELIMINATED

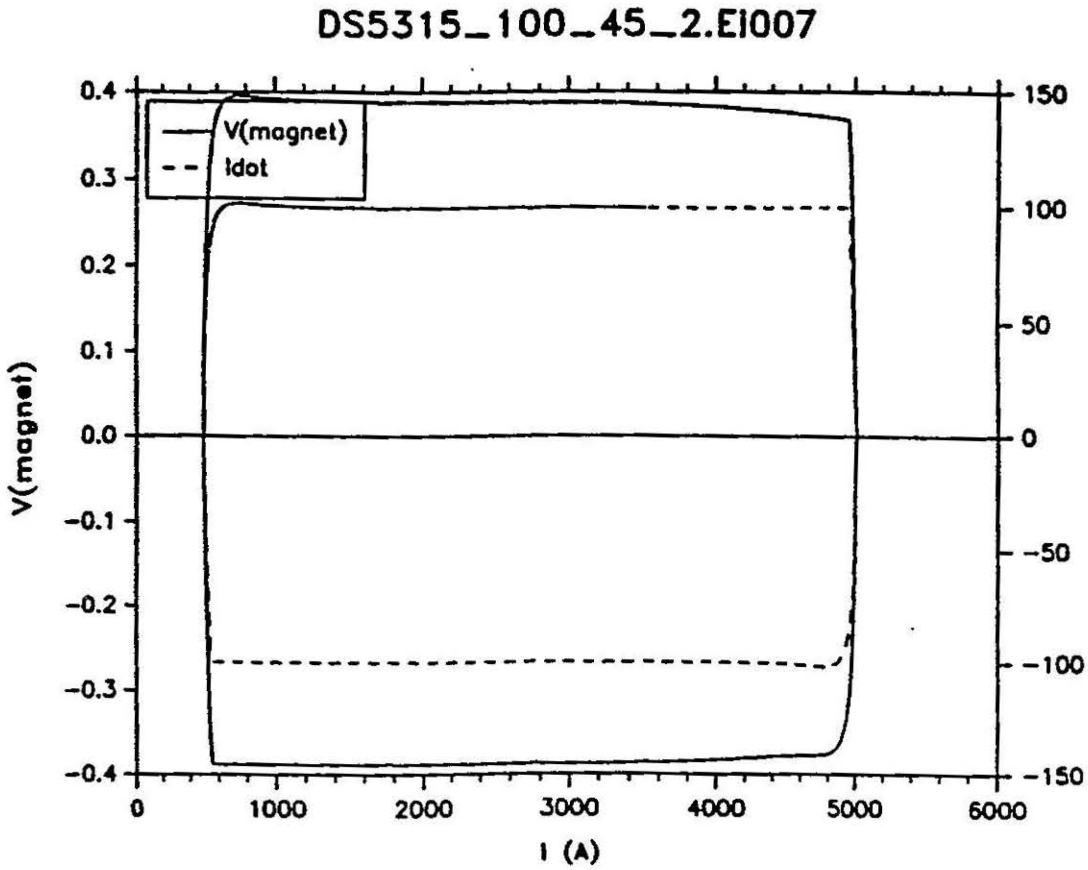
RESULTS :

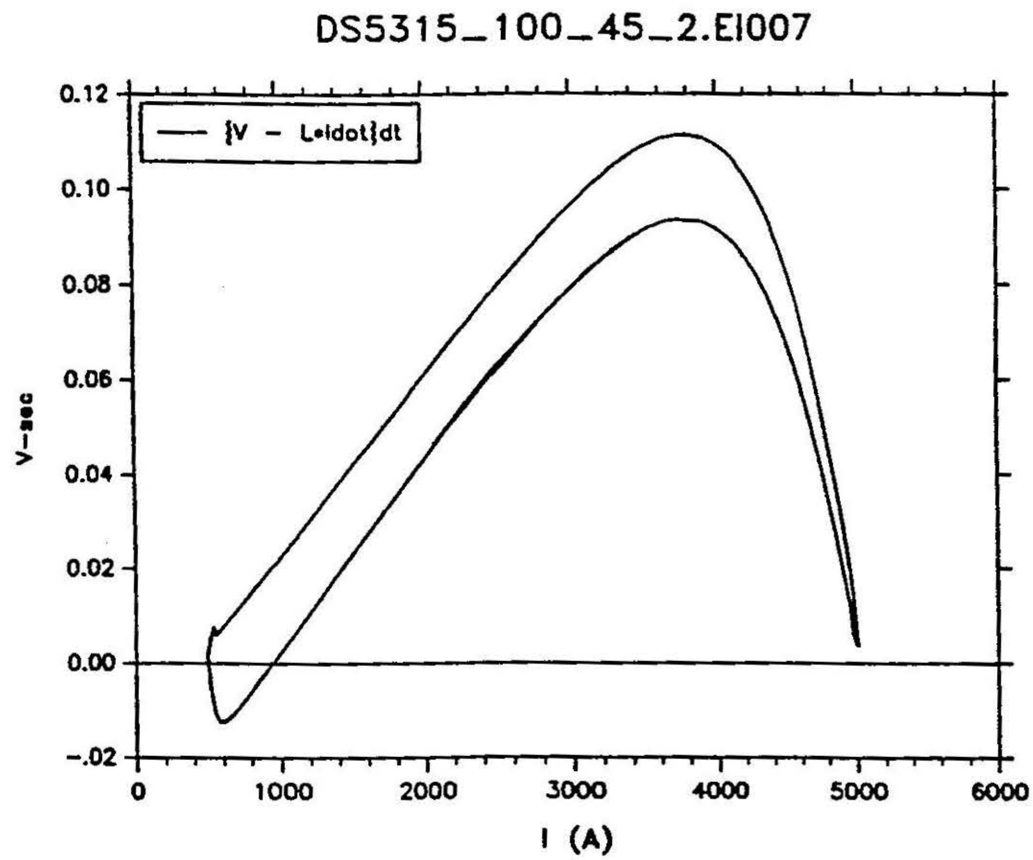
- BEST REPRODUCIBILITY OBTAINED WITH NPLC = 10, AND f_r = 4.5 Hz
- ΔE FOR DC RUNS IS SMALL (≈ 1 J)
- GRAPHICAL ANALYSIS OF $\int V dt$ YIELDS A FIGURE-OF-MERIT CRITERION : DISCONTINUITIES IN $\int V dt$ RESULT FROM NOISE IN V_{MAG} AND YIELD AN ADDED (FALSE) CONTRIBUTION TO ΔE
- NO APPARENT BENEFIT TO USING THE "BUCKING" COIL
  - AS LONG AS THE CRITERION DESCRIBED ABOVE IS FULFILLED, NO DIFFERENCE IN ΔE
- FLATTOPS @ I_{MIN} AND I_{MAX} IMPROVE THE "ROBUSTNESS" OF THE DATA ANALYSIS ALGORITHM - REDUCED ERRORS IN DETERMINING THE ENDPOINTS OF AN INTEGRATION CYCLE
- "REASONABLE" VALUES FOR HYSTERESIS LOSS AND RAMP RATE DEPENDENCE

THESE PRELIMINARY RESULTS WERE ENCOURAGING, AND INDICATED THAT FURTHER STUDY WAS WARRANTED...

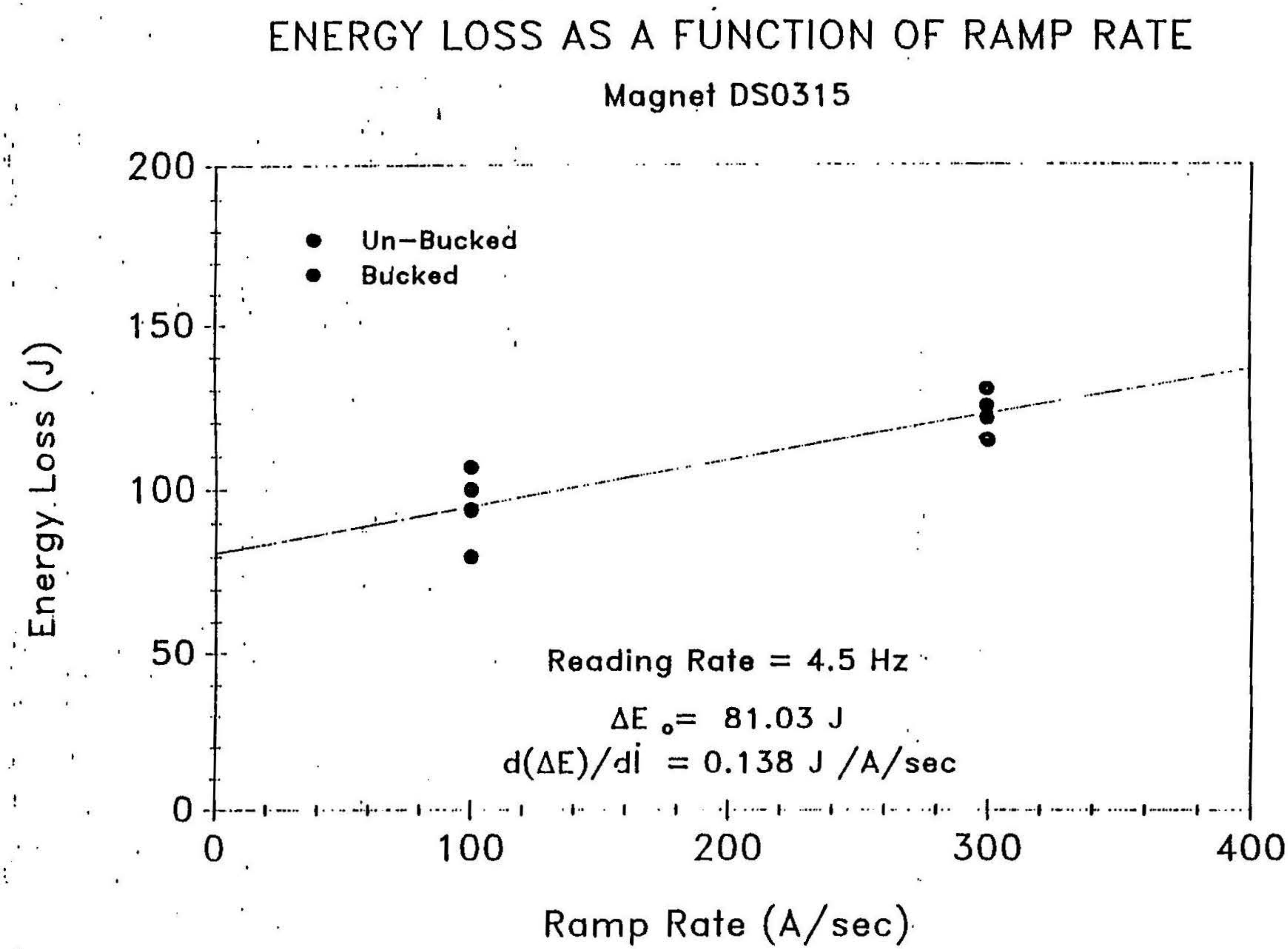

DS2315_030_45_1.EI004
V(magnet)
Idot
V(magnet)
Idot (A/s)
I (A)
DS2315_030_45_1.EI004
∫V – L*Idot∫dt
V-sec
I (A)

"BAD" RUN


DS5315_100_45_2.EI007
V(magnet)
Idot
V(magnet)
Idot (A/s)
I (A)


DS5315_100_45_2.EI007
{V - L*Idot}dt
V-sec
I (A)

"GOOD" RUN



ENERGY LOSS AS A FUNCTION OF RAMP RATE
Magnet DS0315
Un-Bucked
Bucked
Energy Loss (J)
200
150
100
50
0
0
100
200
300
400
Ramp Rate (A/sec)
Reading Rate = 4.5 Hz
ΔE o= 81.03 J
d(ΔE)/dİ = 0.138 J /A/sec

THIRD MEASUREMENT EFFORTS (MAGNET DS0315 - AGAIN)

GOALS :

- MEASUREMENTS OF ΔE AS A FUNCTION OF RAMP RATE (dI/dt = 30, 50, 100, 150, 200, 250, 300 A/sec) USING OUR "STANDARD" RAMP : 500 - 5000 - 500 A

- MEASUREMENTS WITH I_{MAX} = 6500 A (REQUIRED MODIFICATIONS TO PS CONTROLLER)

- STUDY EFFECTS OF LOW RESISTANCE TO GROUND AT VARIOUS POINTS IN THE MEASUREMENT CIRCUIT

- ADDED LOSS MECHANISM - Cu BAR INSERTED IN BORE OF MAGNET, TO DETERMINE SENSITIVITY AND ACCURACY

- UNIPOLAR RAMP RATE STUDIES WITH I_{MIN} = 50 A, RATHER THAN 500 A

- BIPOLAR TESTS, USING :

  --- "STANDARD" RAMPS : 0 ± 5000 A, VARIOUS RAMP RATES

  --- SSC "HEB" RAMPS

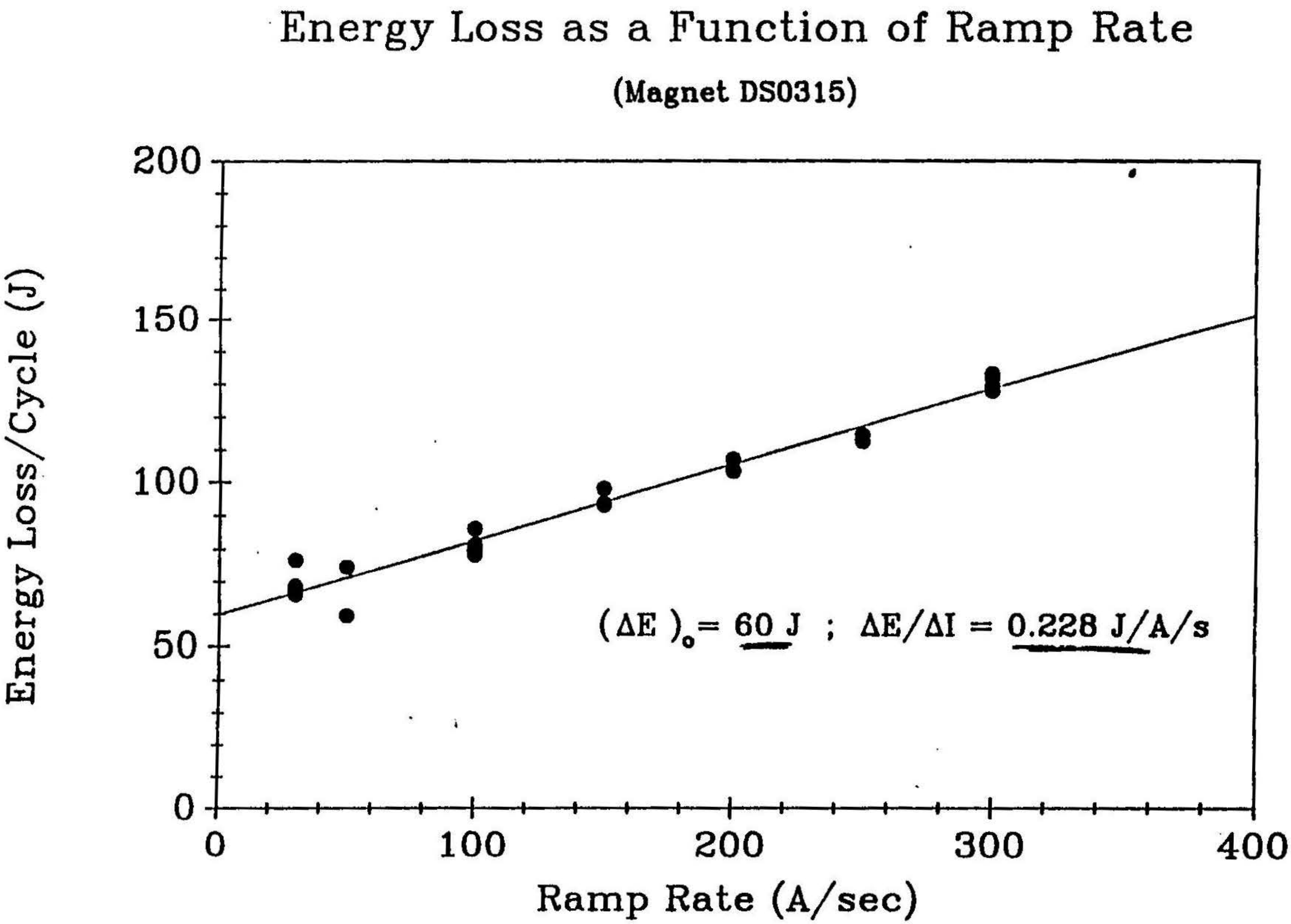
RESULTS :

- ΔE vs dI/dt RESULTS LOOK QUITE REASONABLE - WE GET A HYSTERESIS LOSS OF ABOUT 60 J, AND A RAMP RATE DEPENDENCE OF ABOUT 0.220 J/A/sec

- MEASUREMENTS WITH I_{MAX} = 6500 A ARE REASONABLE ΔE = 100 J @ dI/dt = 100 A/s (compare to 84 J for "std" ramp @ dI/dt = 100 A/s)

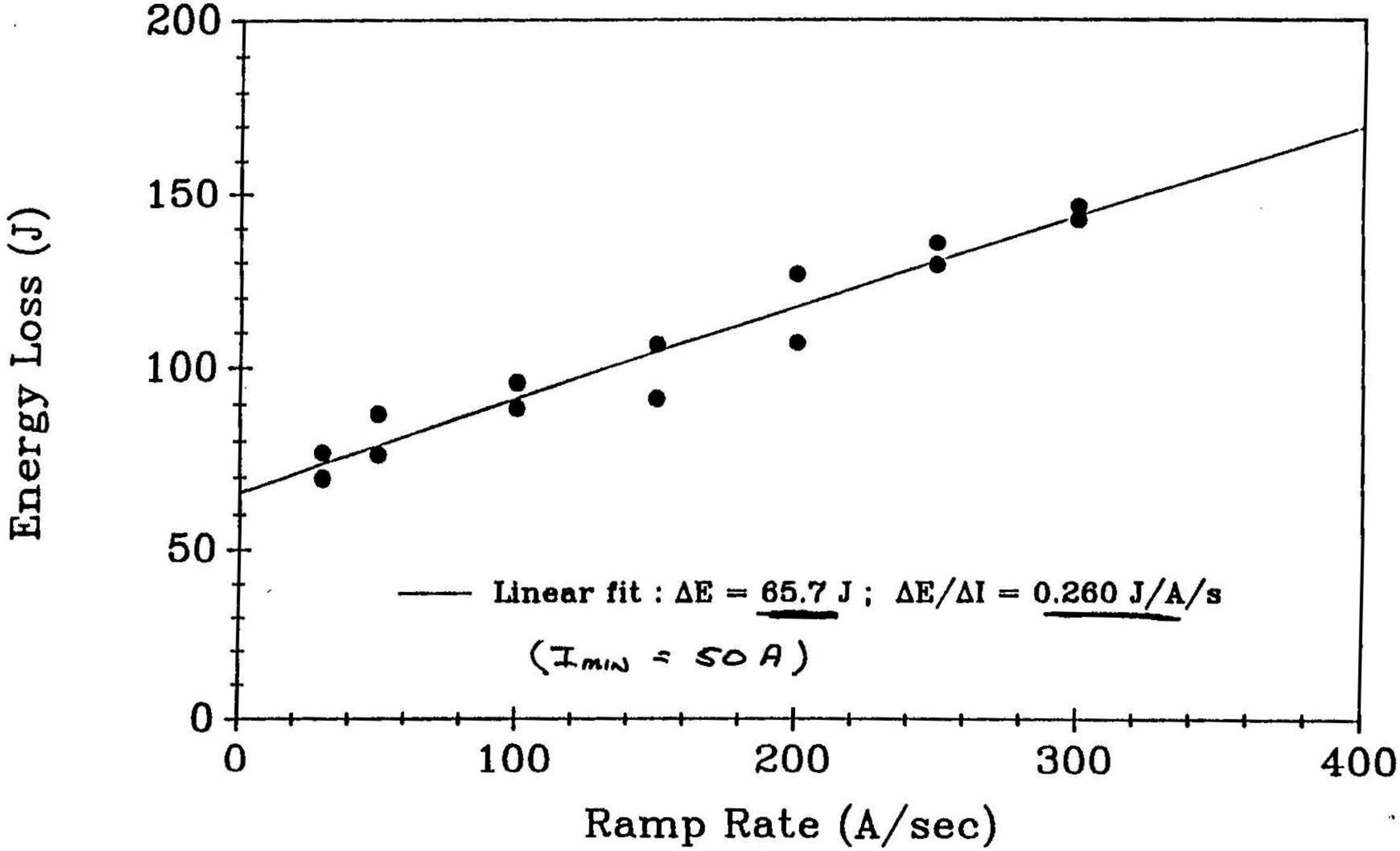
- NO OBSERVED EFFECT WHEN SYSTEM RESISTANCE TO GROUND IS CHANGED AT VARIOUS POINTS IN THE CIRCUIT - VARIATION IN LOSS MEASUREMENT IS 5 J, COMPARABLE TO OUR REPRODUCIBILITY

- UNIPOLAR RAMPS WITH I_{MIN} = 50 A : SHOWS BOTH LARGER HYSTERESIS LOSS (66 J) AND LARGER RAMP RATE DEPENDENCE (0.260 J/A/sec)


Energy Loss as a Function of Ramp Rate
(Magnet DS0315)
Energy Loss/Cycle (J)
200
150
100
50
0
0
100
200
300
400
Ramp Rate (A/sec)
(ΔE)o= 60 J ; ΔE/ΔI = 0.228 J/A/s

Energy Loss as a Function of Ramp Rate

(Magnet DS0315)



• COPPER BAR STUDIES :

— ADDED LOSS SCALES AS CONDUCTIVITY (σ);

THE POWER DISSIPATED IS GIVEN BY :

TYPICAL EDDY CURRENT LOSS

$$P = ((\sigma \dot{B}^2 w^3 h)/12)L \qquad \text{(Lamm, Haddock)}$$

WHERE σ = conductivity, L = length of bar,
w = width of bar, h = height of bar,

CALCULATIONS SHOWED THAT ADDED LOSS AT ROOM TEMPERATURE TO BE BELOW MEASUREMENT SENSITIVITY

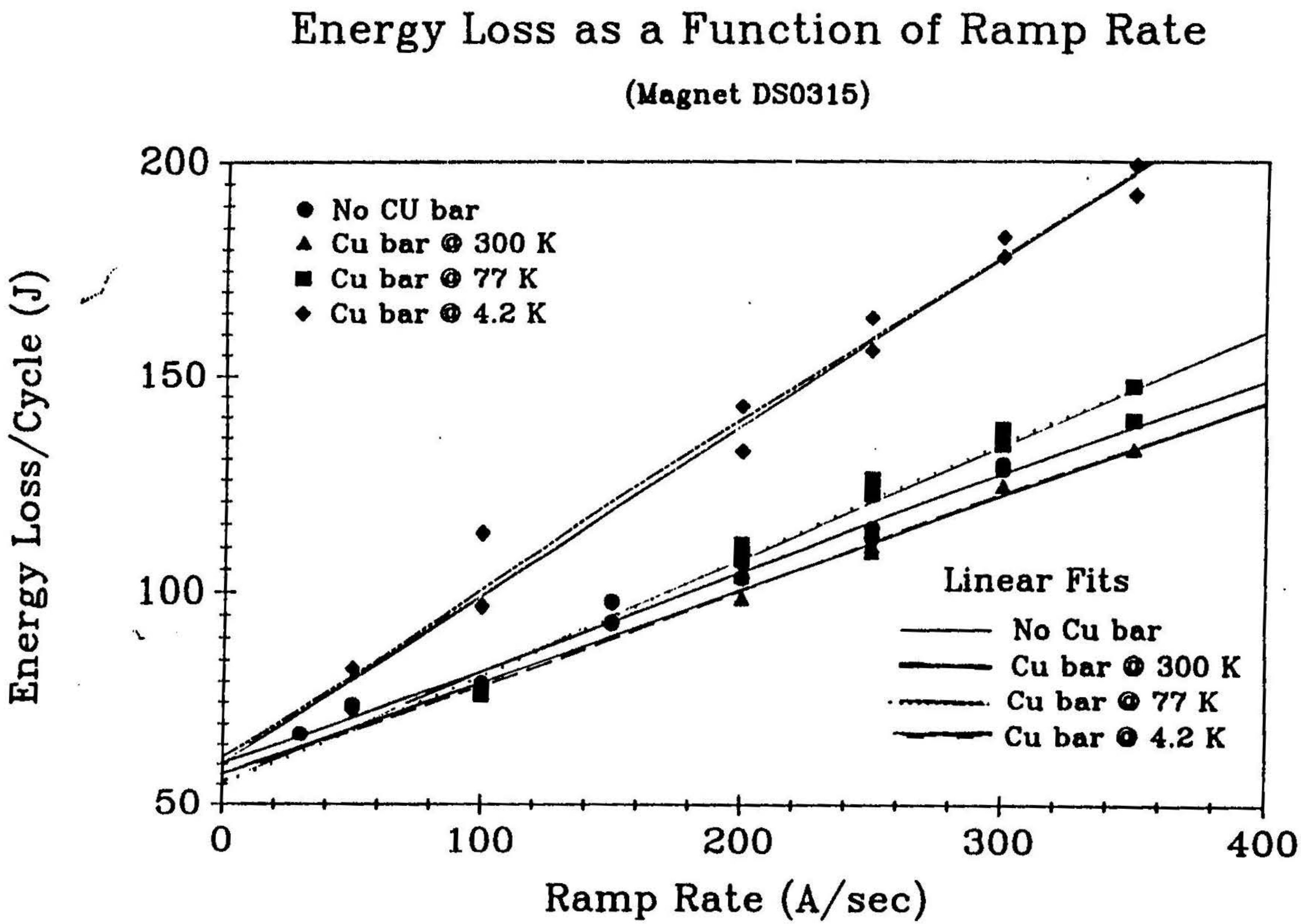
∴ PERFORM MEASUREMENTS AT 77 K, 4.2 K

MEASURED AND EXPECTED ADDED LOSS (ΔE^*) FOR OUR "STANDARD" RAMP @ 100 A/sec :

T (K)	ρ (= 1/σ)	ΔE^*_{CALC} (J)	ΔE^*_{MEAS} (J)
300	1.71 E-8	0.4	≈ 0
77	~~1.4 E-9~~ 2.32E-9	~~5~~ 3.0	≈ 3 – 4
4.2	~~3 E-10~~ 3.1 E-10	~~23~~ 22.3	≈ 20

NEWS FLASH! → MEASURED VALUES

THESE RESULTS ARE QUALITATIVELY IN GOOD AGREEMENT - WE MUST MEASURE σ OF OUR BAR AT 77 K AND 4.2 K TO ACHIEVE A MORE ACCURATE COMPARISON



Energy Loss as a Function of Ramp Rate
(Magnet DS0315)
No CU bar
Cu bar @ 300 K
Cu bar @ 77 K
Cu bar @ 4.2 K
Linear Fits
No Cu bar
Cu bar @ 300 K
Cu bar @ 77 K
Cu bar @ 4.2 K
Energy Loss/Cycle (J)
Ramp Rate (A/sec)
200
150
100
50
0
100
200
300
400

- BIPOLAR STANDARD RAMP : RAMP RATE STUDY WITH dI/dt = 60, 100, 150, 200, 250, 300 A/sec; SYMMETRIC RAMP WITH 5 SECOND DWELLS AT I_{MIN}, I_{MAX}, AND AT I = 0

  (DWELL AT I = 0 IS DICTATED BY BIPOLAR SWITCH OPERATION)

  RESULTS :

  HYSTERESIS LOSS = 188 J

  RAMP RATE DEPENDENCE = 0.35 J/A/sec

  QUALITATIVELY, THIS SEEMS REASONABLE ---

  QUANTITATIVELY, WE HAVE NO REAL CALCULATIONS FOR COMPARISON

- BIPOLAR SSC "HEB" CYCLES : RAMP IS A COMPLEX BI-POLAR RAMP SUPPLIED BY SSCL, BEING CONSIDERED FOR USE IN THE HEB... CURRENT RANGE IS +/- 6400 A, WITH FLATTOPS AT I_{min} AND I_{max} , AND AT I = 0.

  WE MEASURED AC LOSS AS A FUNCTION FO RAMP RATE FOR dI/dt = 90, 113, 170, 226, 283, AND 339 A/sec.

  RESULTS :

  HYSTERESIS LOSS : 212 J

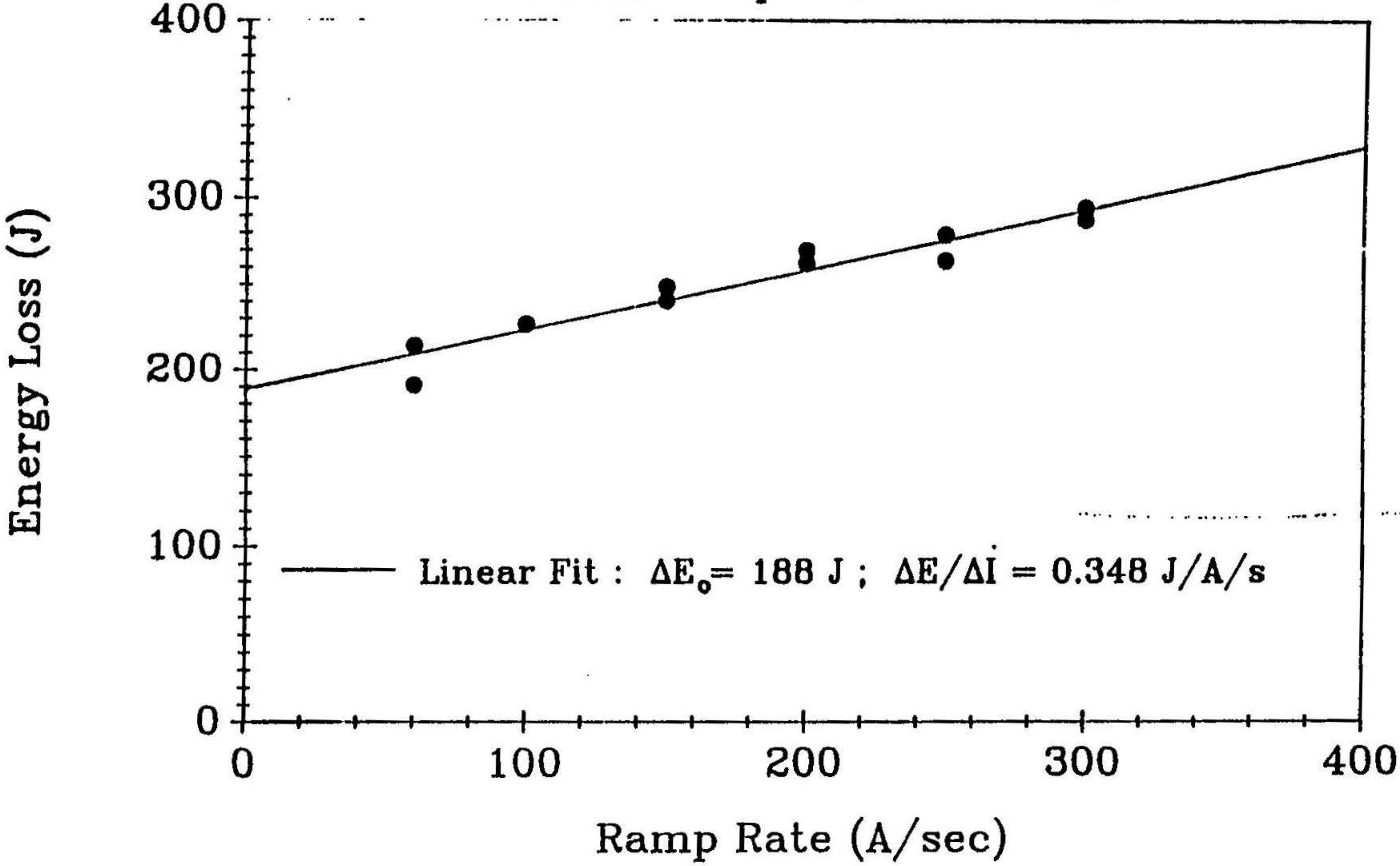
  RAMP RATE DEPENDANCE : 0.563 J/A/sec

- AGAIN, IT SEEMS REASONABLE : NEED CALC'S !

Energy Loss as a Function of Ramp Rate

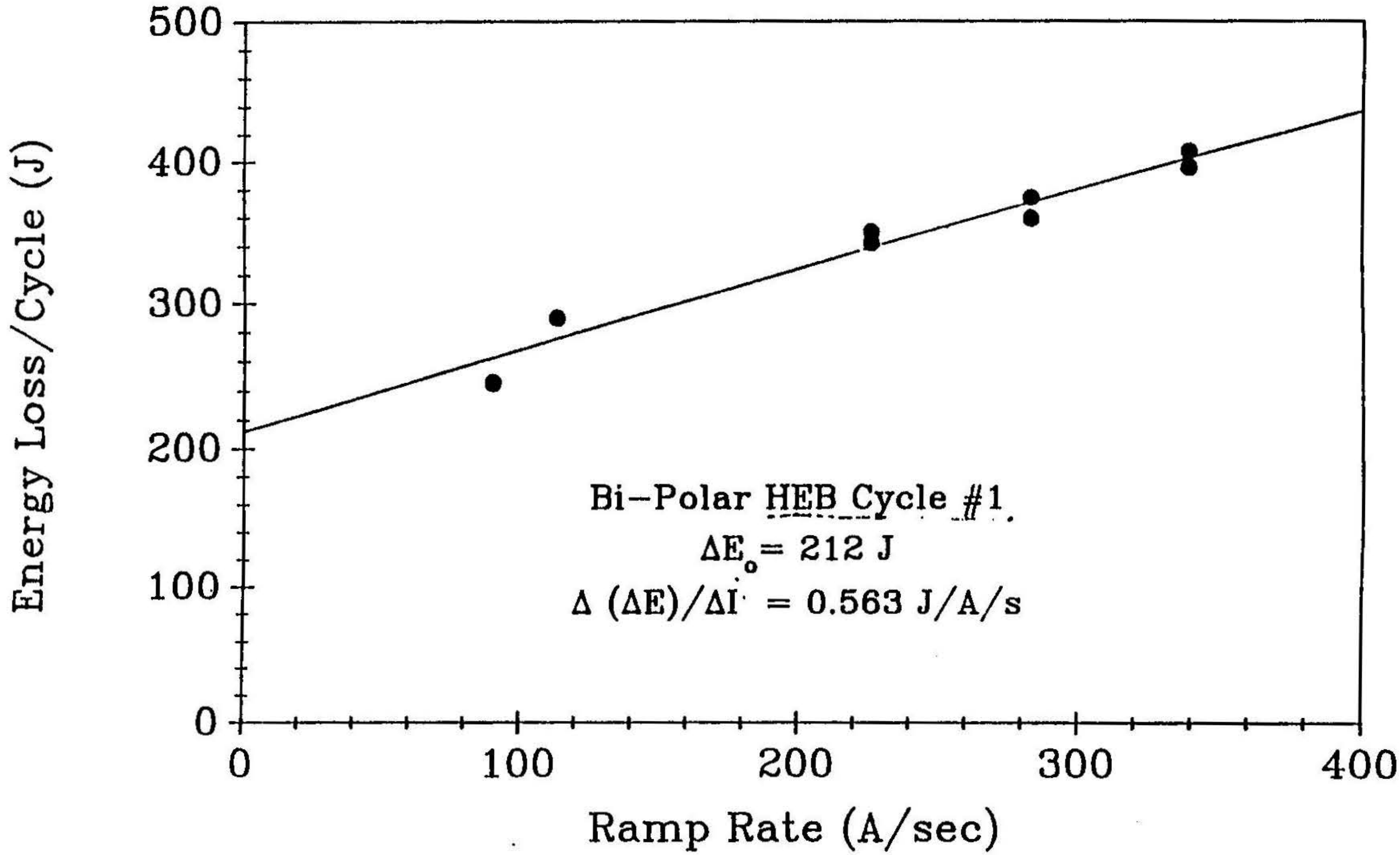
(Magnet DS0315)

" STD." Bi–Polar Ramps : 0 ⟶ ± 5000 A



Energy Loss as a Function of Ramp Rate

(Magnet DS0315)



NOW - ON TO...

HARMONICS MEASUREMENTS :

THE MAGNETIC FIELD CAN BE DESCRIBED AS AN INFINITE SERIES OF "MULTIPOLES" ...

$B_y - iB_x = \Sigma (B_n - iA_n)((x + iy)/r_o)^n$ for $n = 0 \longrightarrow \infty$

where A_n and B_n are the skew and normal coefficients, and r_o is the reference radius, chosen as 1cm for SSC dipoles.

The x and y directions are chosen so that A_o is zero for $I \neq 0$ and B_o is +ve for I = +ve.

MAGNETIC FIELD HARMONICS MEASUREMENTS WERE PERFORMED ON MAGNET DS0315 USING OUR "STANDARD" UNIPOLAR AND BIPOLAR RAMPS...

1.) I = 500A ---> 5000A ---> 500A,

2.) I = 50A ---> 5000A ---> 50A, and

3.) I = 0A ---> 5000A --->0A ---> - 5000A ---> 0A

at dI/dt = 100 A/sec.

FIELD HARMONICS WERE MEASURED USING THE STANDARD LAB2 MAGNETOMETER - 6Hz ROTATING MORGAN COIL, V/F CONVERTERS, ETC....

RESULTS :

THE ORIGIN OF HYSTERESIS IN THE MAGNETIC MULTIPOLES IS THE HYSTERESIS IN THE SUPERCONDUCTOR --- IT IS MOST EASILY OBSERVED IN THE NORMAL SEXTUPOLE (B_2) .

FROM THE PLOTS OF B_2 AS A FUNCTION OF CURRENT, WE FIND :

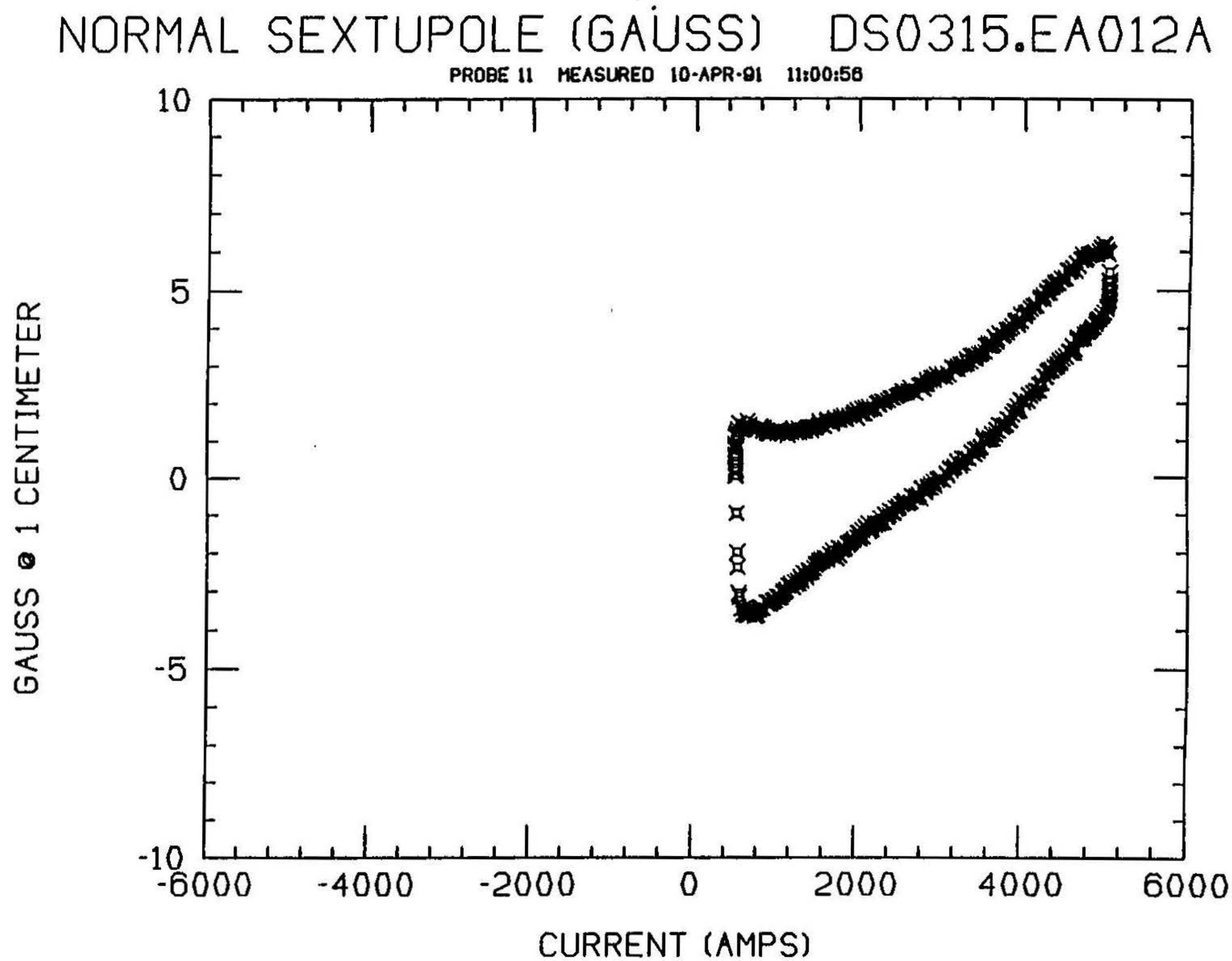
1.) THE SEXTUPOLE SHOWS INVERSION SYMMETRY, i.e.,

$$B_2(I) = -B_2(-I)$$

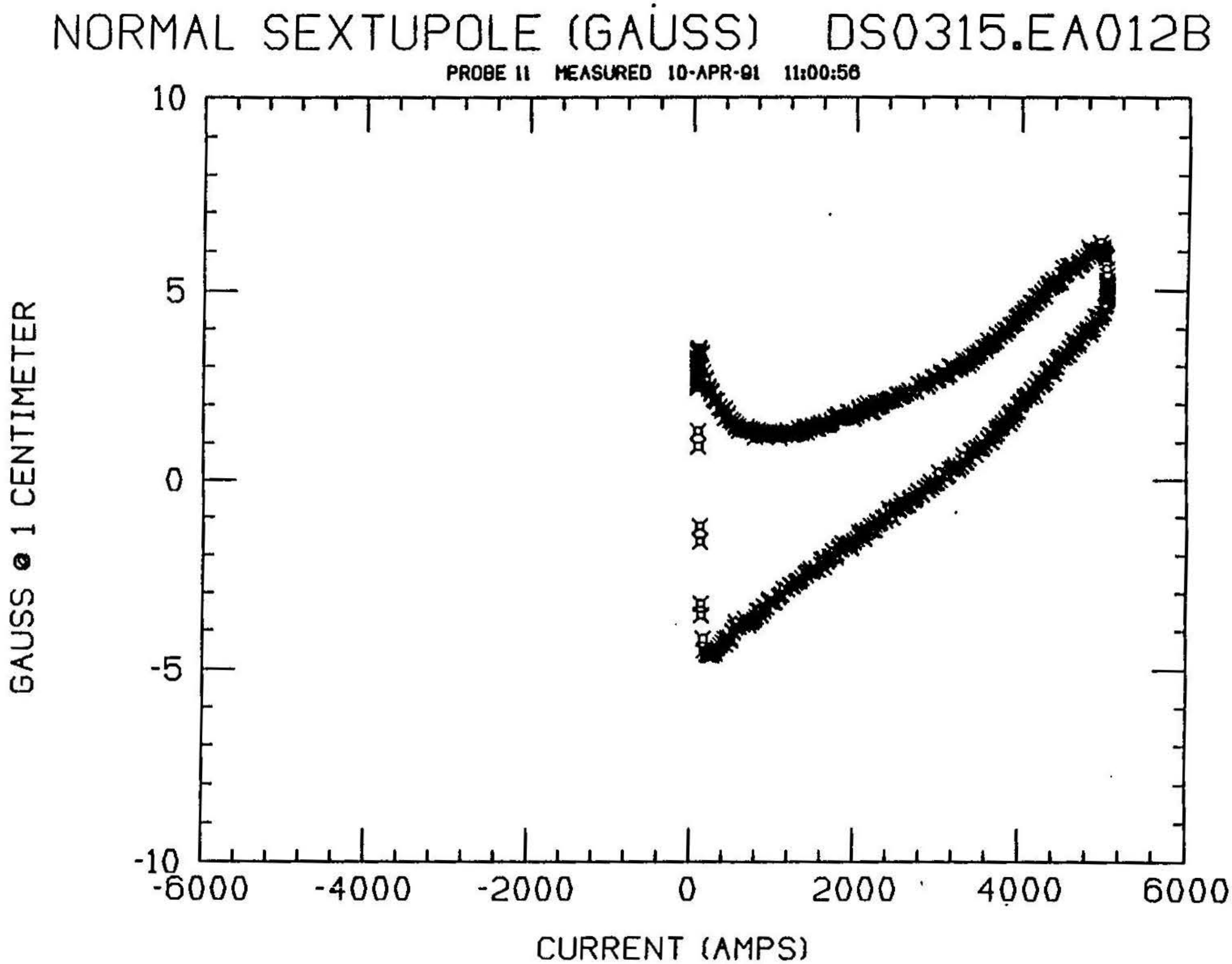
2.) UNIPOLAR B_2 CURVES LIE ON TOP OF BIPOLAR B_2 CURVE - NO APPARENT DEVIATION IN B_2 AS A FUNCTION OF RAMP RANGE, TYPE.

SO... NO REAL SURPRISES HERE.

(NOTE : B_2 HAS NOT BEEN NORMALIZED - B_0 VANISHES @ $I=0$ ...)



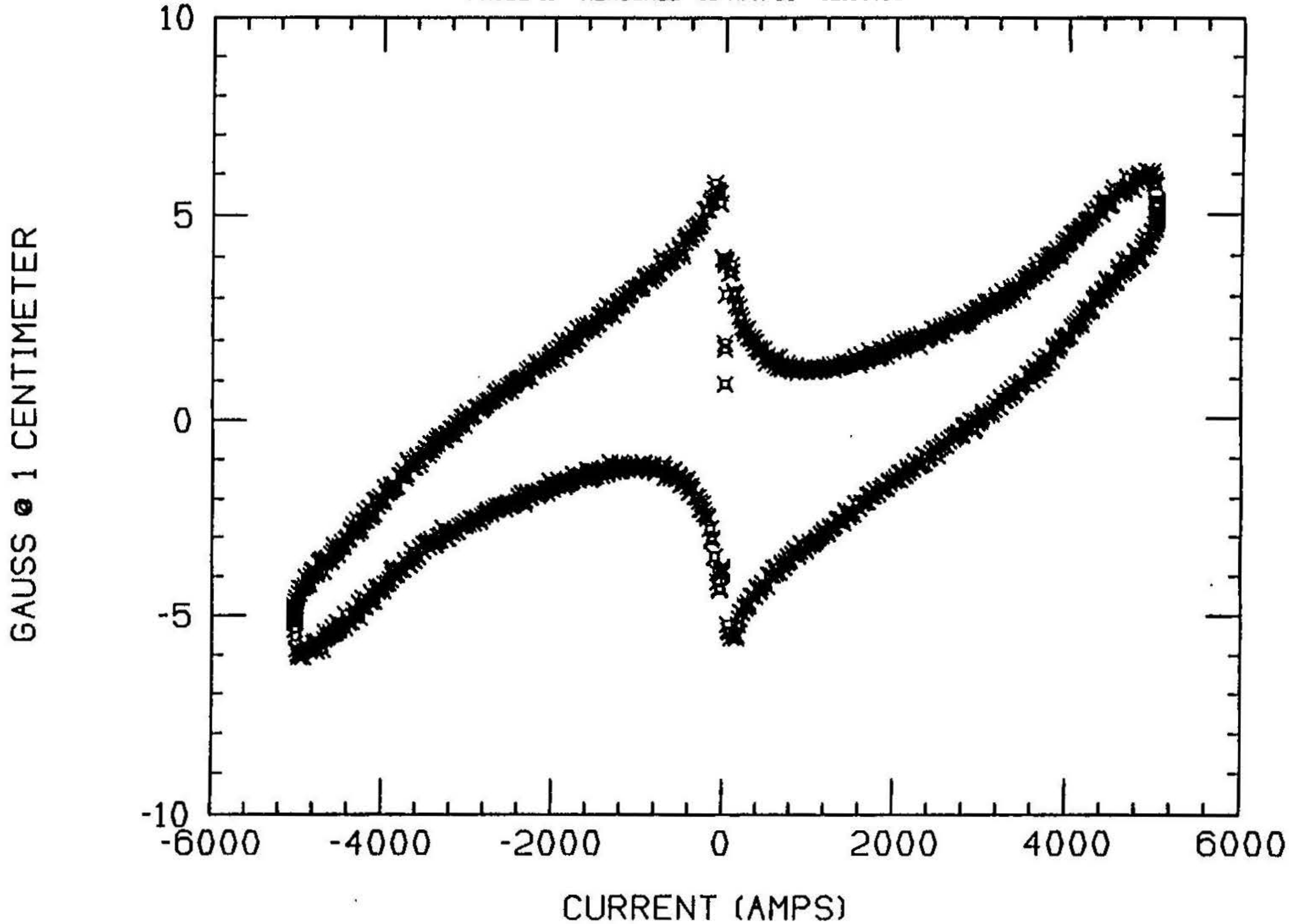
Unipolar (500 → 5000A) Ramp



UNIPOLAR (50 → 5000 A) RAMP

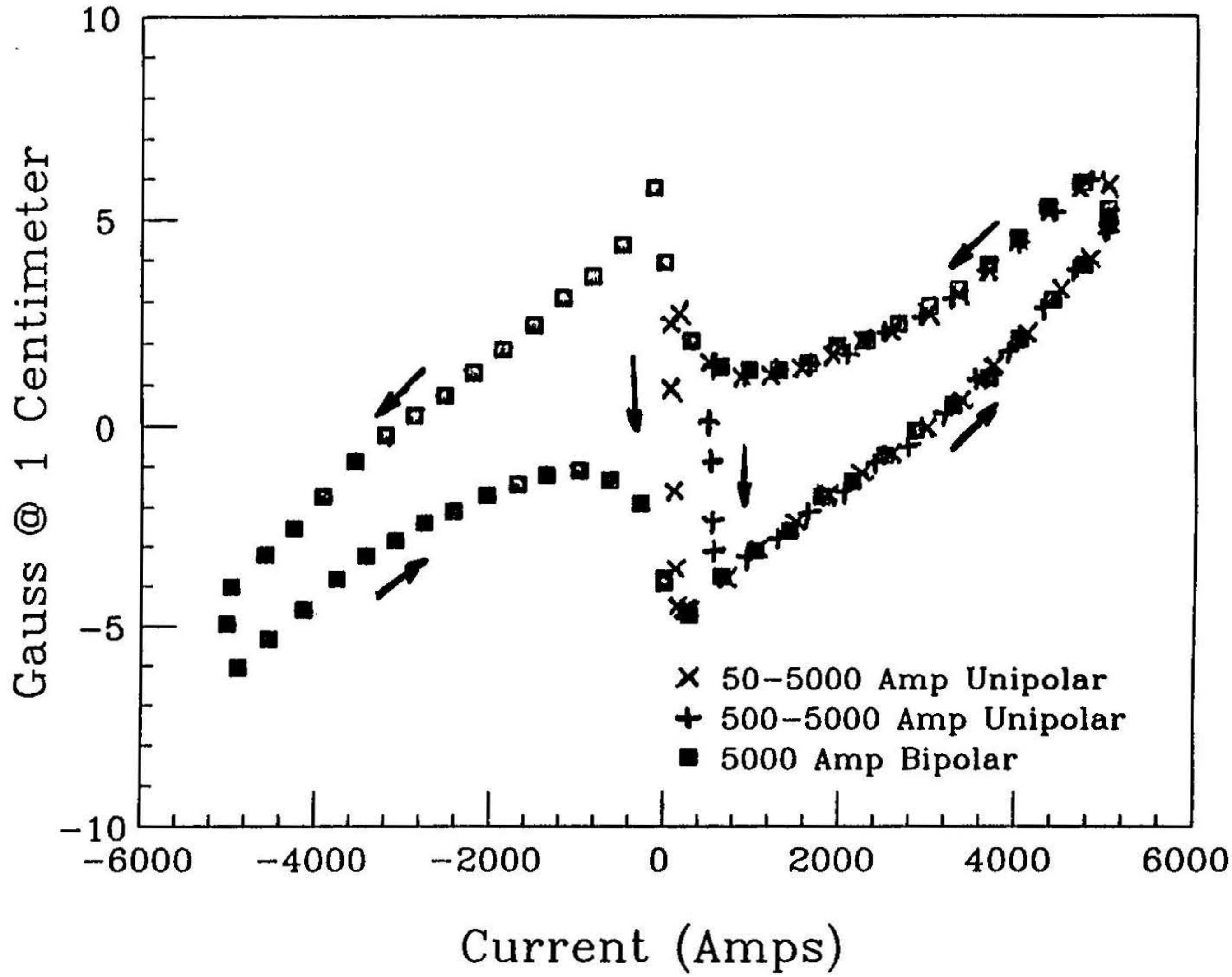
NORMAL SEXTUPOLE (GAUSS) DS0315.EA013

PROBE 11 MEASURED 10-APR-91 12:36:58



BIPOLAR (0 —> ± 5000 A) RAMP

COMPOSITE PLOT w/ 3 RAMP TYPES :



CONCLUSIONS :

AC LOSS MEASUREMENT TECHNIQUE SEEMS REASONABLE - GET GOOD AGREEMENT BETWEEN EXPECTED RESULTS AND MEASUREMENTS, WHERE CALCULATIONS EXIST.

SIGNAL INTEGRITY IS OF PRIME IMPORTANCE IN ENSURING VALID, REPRODUCIBLE RESULTS.

BIPOLAR LOSSES ARE GREATER THAN UNIPOLAR LOSSES. AS EXPECTED, BOTH THE SC AND IRON HYSTERESIS AND THE EDDY CURRENT LOSSES ARE GREATER UNDER BIPOLAR OPERATION.

THE FIELD HARMONICS OBEY INVERSION SYMMETRY, i.e, $B_n (I) = - B_n (-I)$, AS EXPECTED.

FUTURE STUDIES :

UNIPOLAR AND BIPOLAR LOSS STUDIES ON 50mm SHORT MAGNETS (DSA324, DSA326...), USING OUR "STANDARD" CYCLES, AND SSC HEB CYCLES.

COMPARISON W/ CALCULATIONS...

MEASUREMENT SYSTEM IMPROVEMENTS (DATA RATE, SOFTWARE, SIGNAL FILTERING...)

AND IN A RELATED VEIN....STUDIES OF $B_2(t)$ AFTER BIPOLAR CYCLES ?

→ PERSISTENT CURRENT EFFECTS UNDER BIPOLAR OPERATION – WE KNOW THAT $B_2(t)$ DEPENDS UPON HISTORY !