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STATUS OF AC LOSS MEASUREMENTS OF 1.5m SSC MODEL DIPOLE MAGNETS AT FERMILAB

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Introduction

Over the past several months, measurements of AC losses have been performed at FNAL on several 1.5m SSC model dipole magnets. Initial measurements on magnet DS0315, the last 40mm diameter bore short model magnet, were aimed at evaluating the measurement system and determining such factors as measurement reproducibility and accuracy. Later measurements, on magnets DS0315 and DS0314, offered reasonably accurate data regarding the losses in these magnets when operated under various unipolar and bipolar ramp conditions. The latest extensive round of measurements, performed on magnet DSA324, offer evidence of substantially larger losses in the 50mm bore magnets under various ramp types, while at the same time demonstrating evidence of very good reproducibility and sensitivity of the measurement system. This report will describe in detail the measurement system, recent measurements and their results, and avenues for future investigations.

Measurement System

The technique employed at FNAL for measuring hysteresis and eddy current losses differs from previous techniques employed here and elsewhere. Previous methods either required the analog integration of the product of the magnet voltage and current[1,2,3], or calorimetric measurements of the heat produced by these loss mechanisms[4,5]. The former methods suffered from problems of drift of the analog integration circuitry, and required the use of a "bucking" coil in series with the magnet, to subtract off the large inductive component fro the magnet voltage signal. The latter methods require very careful control and knowledge of the various heat loads in the cryogenic system, and elimination of any heat leaks that are present. Even former digital integration techniques[6] still required the use of a bucking coil, and were therefore prone to errors induced by the extra circuitry this technique requires, and noise that can be picked up in such a coil from the electromagnetic environment.

The measurement system in use at FNAL comprises two fast, integrating digital voltmeters (Hewlett-Packard model 3457A), which simultaneously record the voltage across the total magnet coil, and the magnet current (via a 12kA shunt). The DVM's are triggered simultaneously by a function generator (Wavetek model 75), which outputs a burst of pulses to the external trigger input of the DVM's. A reading is initiated for each pulse received. Simultaneous external triggering of the two voltmeters ensures that the magnet voltage and current are measured at precisely the same instant of time. Passive low-pass filters (100 Hz or 4 Hz) are used on the inputs of the DVM's to suppress 720Hz noise that results from the firing pattern of the SCR's in the Transrex magnet power supplies. An IBM-PC type computer (with 80386 processor operating at 20MHz) is used to control the data acquisition process, utilizing the GPIB bus for data transfer and instrument control. Figure 1 indicates the relevant components of the AC loss measurement system. Magnet voltage and current are digitally integrated offline to yield energy loss per closed current cycle, using data analysis software written in Fortran and run on the FNAL central Vax cluster. Data can also be analysed using a complementary program, written in compiled Basic, on the PC. Agreement between these two analysis programs is typically better than 1 Joule (< .5 %), the discrepancy being ascribed to differences in real number handling between the two computer systems. In addition to energy loss results, the Fortran data analysis program also provide the capability to plot various voltage/current/time relationships.

Measurement Procedure

During a typical AC loss measurement run, the magnet is cooled to 4.2K by insertion in a bath of boiling liquid Helium. The magnet is powered using a single Transrex 500-5 unipolar power supply; bipolar operation can be achieved using a current-reversing switch developed for the Fermilab D0 low-ß insertion project. The power supply is controlled using a DEC µVax through CAMAC and GPIB busses. The DVM's are triggered at a frequency of 4.5 Hz , corresponding to a DVM integration time of 10 power-line cycles, and a sufficient number of readings to capture a complete ramp cycle are taken. Individual readings are stored in the internal memory of the DVM's in FIFO mode, and read out by the PC.

A standard unipolar ramp consists of a 5 second dwell at 500 A, a linearly ascending ramp to 5000 A, a 5 second dwell at 5000 A, then a linearly descending ramp to 500 A. This cycle is performed at least 10 times for each ramp rate studied, measurements being initiated on the 4th and subsequent cycles. Unipolar cycles are studied at ramp rates from 30 to 300 A/second.

Standard bipolar ramp cycles consist of a 5 second dwell at 0 A, then a linear ramp to 5000 A, a 5 second dwell at 5000 A, then a linear ramp to 0 A. After a 5 second dwell at 0 A (dictated by the operational characteristics of the bipolar switching circuit), the current is reversed and the magnet is ramped to -5000 A. After a 5 second dwell at -5000 A, the magnet is then ramped to 0 A. This bipolar cycle is also performed at least 10 times, with data being taken on the 4th and subsequent cycles, at ramp rates ranging from 60 to 300 A/sec.

AC Loss Measurements - Magnet DS0315

Magnet DS0315, a 1.5m model dipole, was the last FNAL-built short 40mm magnet and was tested extensively. Complete test results and construction details are available elsewhere[7,8]. This magnet was used during the development of the digital AC loss measurement technique, and provided a benchmark for measurement reproducibility, etc. The results of the first round of measurements were reported earlier[9]. For example, through measurements performed on this magnet, it was found that a bucking coil was not necessary for the success of the digital integration technique. Measurements with and without the bucking coil differed by less than 5%, which was the same as the measurement reproducibility at that time. It was also found that low-pass filters were needed to eliminate the 720 Hz noise from the power supplies. A discontinuity in the current versus time relationship was seen when operating with two power supplies in parallel (the standard test configuration), which led to errors in the magnet voltage integration. Therefore, it was decided to use only one power supply for all subsequent AC loss measurements, eliminating this possible source of error. We also experimented with different integration times and data sampling rates, finally settling upon a data rate of 4.5 Hz and a 10 power-line cycle integration time. (It should be noted that this integration time does not refer to the integration of the magnet voltage and current, but to the time that the voltmeter integrates the input reading, eliminating random noise contributions, while taking into account any actual changes in the input signal.)

The second round of AC loss measurements yielded reliable quantitative results. Under a standard unipolar cycle (from 500 to 5000 A), the hysteresis loss (identified as the loss at zero ramp rate) was measured as 60 Joules, with a ramp rate dependence of 0.22 Joules/A/sec. These results are plotted in Figure 2. In Figure 3 the results of a similar measurement, from 50 to 5000 A, are given. Note that both the hysteresis loss and eddy current loss have increased in this case, as a result of the larger range in current for this particular cycle. In the latter case the hysteresis loss is now about 66 Joules, with a ramp rate dependence of 0.26 Joules/A/sec.

Under operation with a standard bipolar ramp cycle, spanning the current range ± 5000 A, we find a significantly larger energy loss per cycle. From Figure 4 we find a hysteresis loss of about 188 Joules, about a factor of 3 increase, with a ramp rate dependence of about 0.35 Joules/A/sec. These results are in very good qualitative agreement with expectations; we expect a greater hysteresis loss in the iron yoke under bipolar operation, and an increase in the eddy current dependence by a factor of about 2.

Measurements were also performed for a different bipolar cycle, supplied by the SSCL, and designated bipolar HEB cycle #1. This particular ramp was slightly more complex than those used previously; it included dwells at ± 640 A, ± 6400 A, and at 0 A. Energy losses over this cycle were studied for ramp rates from 90 to 339 A/sec. Due to the much larger current range in this cycle, it was expected that both the hysteresis losses and eddy current losses would be larger than for the standard bipolar cycle. From Figure 5 we see that this is indeed the case - the hysteresis loss has increased to 212 Joules, while the ramp rate dependence is now 0.56 Joules/A/sec.

AC Loss Measurements - Magnet DS0314

The second magnet to undergo AC loss measurements was magnet DS0314, also a 1.5m model magnet with a 40mm bore. This magnet, though built before DS0315, was tested later due to poor initial quench performance which required disassembly and correction. The construction details are similar to those of DS0315, and complete performance results have been presented in an earlier note[10].

Due to time constraints, the only AC loss measurements performed on this magnet were the standard unipolar ramp rate study. Results of these measurements were somewhat discouraging, as the scatter in the data was quite large. This was attributed to electrical noise in the magnet voltage signal, perhaps due to poor shielding of the signal leads, and inductive pick-up. Even so, the results obtained from a fit to the data yield a hysteresis loss of about 85 Joules, and an eddy current dependence of about 0.23 Joules/A/sec. These figures are in relatively good agreement with those obtained from measurements on magnet DS0315.

AC Loss Measurements - Magnet DSA324

Magnet DSA324 is the fifth short model magnet with a 50mm bore to be built at FNAL, and the third such magnet to undergo cold testing. Details of its design and performance have been previously documented[11,12]. It was the first 50mm magnet to be measured for AC losses. Since more time was available than normally, various special tests were performed on this magnet in addition to the now standard unipolar and bipolar ramp rate studies.

Standard Measurements

Figure 6 indicates the results of a standard unipolar ramp rate study. The much higher hysteresis loss of this magnet is clearly evident, as is the larger ramp rate dependence. This magnet experiences a hysteresis loss in this cycle of 109 Joules, about 70% more than a 40mm magnet. This is not unreasonable, as the hystersis loss scales with the volume of the superconductor, which is greater in a 50mm magnet. Likewise, the ramp rate dependence of 0.70 Joules/A/sec is also significantly higher than that of a 40mm magnet; increased amounts of copper from the longer, wider cable is most likely the cause here. It should be noted that magnet DSA324 showed a poorer dependence between ramp rate and quench current, i.e., the degradation in quench current occurred at lower ramp rates than for other 50mm and 40mm magnets. This was attributed to the cable itself, which showed a lower strand to strand resistivity. This property would also contribute to larger eddy current losses.

The other standard test performed on this magnet was the bipolar ramp rate study. The results of these measurement are presented in Figure 7. The hysteresis loss for the bipolar cycle has increased to 300 Joules, while the eddy current losses have increased substantially to 1.69 Joules/A/sec. As in the case of the 40mm magnets, bipolar operation leads to a much larger hysteresis loss in the iron, again an increase of about a factor of 3. The increase in the eddy current portion is also close to the factor of 2 that we expect. The scatter in the bipolar data is typically about 20 Joules, corresponding to a 2-4 % deviation.

Other Measurements

It had been noted during previous AC loss measurements that an irregularity in the magnet voltage signals was often observed at points corresponding to about 4800-4900 A. It was unknown at the time whether or not this was due to current fluctuations from the power supply, or noise from outside sources. It was also not known whether or not this occurred at some fixed value of the magnet current or at some fixed percentage of the maximum current. To isolate this problem, a unipolar ramp rate study was performed, identical to the standard unipolar ramp, except that the maximum current was 4500 A instead of 5000 A. Analysis of the magnet voltage for this cycle failed to reveal any irregularity, indicating that the current fluctuations of the power supply were confined, for example, to the regime between 4750 and 5000 A. A plot of the loss as a function of ramp rate is given in Figure 8, which shows a hysteresis loss of 93 Joules, and a ramp rate dependence of 0.69 Joules/A/sec. These values compare very favorably with those from the standard unipolar run for this magnet; the hysteresis loss has decreased in proportion to the decrease in current range. Note also that the scatter in the data is substantially less in this case, owing to the fact that irregularities in the magnet voltage, due to current fluctuations above 4500 A, have been eliminated.

Another set of runs were performed where the current range was identical to the standard unipolar run, but the values of I_{min} and I_{max} were changed to 0 and 4500 A, respectively. This run could be compared directly to the standard unipolar run; any differences would result from the change in current endpoints, but not current range. Results are presented in Figure 9. From this plot we see that this run produced hysteresis losses and eddy current losses almost identical to the standard unipolar run, 111 Joules and 0.82 Joules/A/sec., respectively. Both of these values agree extremely well with those from the standard unipolar run, to within our experimental error. Any effects on the hysteresis loss from differences in minimum current are overcome by the fact that the superconductor is eventually exposed to fields in excess of the penetration field.

A third set of non-standard runs were performed, with I_{min} and I_{max} now changed to 0 and 5000 A, respectively. Figure 10, a plot of the data from this run, shows that the hysteresis loss has increased to 132 Joules, while the ramp rate dependence has similarly increased, to 0.80 Joules/A/sec. These values agree well with our expectations based upon the increase in the current range, from 4500 A to 5000 A. Note too, that the scatter in the data is somewhat larger than for the previous runs, due to the irregular contribution from power supply noise above 4500 A.

The final set of runs were designed to determine the dependence of the hysteresis loss on the field change. It is known that for fields less than the so-called penetration field B_p, the loss as a function of field strength varies quadratically. Above this penetration field, the loss scales linearly[13]. In a single strand of superconductor, this transition is quite distinct; in a composite cable, or magnet coil, the transition is expected to be less obvious, due to the fact that not all of the superconducting filaments are experiencing the same field strength at the same current level. To investigate this phenomenon, several runs were performed at a fixed ramp rate (50 A/sec.), to increasingly higher final currents (100, 200, 300, 500, 750, and 1000 A). The hysteresis loss (eddy current losses have been subtracted out) is shown in a log-log plot in Figure 11. The change in dependence upon current range (or field strength) is clearly evident. The region above about 400 A appears to have a slope equal to unity, while the region below 400 A has a higher slope, approximately equal to 2. This behavior agrees well with our expectations, and lends credence to our belief that we are indeed performing reliable and realistic measurements of AC losses.

Conclusions / Remarks

Through various measurements on several different 1.5m model magnets, we have been able to satisfactorily evaluate the performance of the digital integration technique for measuring AC losses. We find that the technique developed at FNAL has become a reliable means for determining the losses in a superconducting magnet under transient operating conditions. The measured losses for the various magnets seem reasonable, and the dependence of the loss on various parameters agree with expectations. The one element of this study that is lacking at present is a thorough comparison of the measurement results with analytical or numerical calculations. This comparison is vital to a complete evaluation of the measurement system's absolute accuracy and systematic errors. Any future work on AC losses should entail a sincere effort to perform calculations of AC losses on 50mm short (1.5m) model dipoles, under the standard ramp cycles (both unipolar and bipolar).

Additional experimental work should be centered around measurements of additional 50mm model magnets, so that some basis for comparison between various magnets and their other performance characteristics (training, ramp rate behavior, etc.), could be obtained. The measurement of only one short 50mm magnet leaves us statistically lacking. Additionally, this measurement process should at some future time be extended to a full length 50mm bore prototype magnet. Measurements on a long magnet will help confirm the belief that the loss should scale linearly with length, and also help determine the contributions of end effects to the overall losses.

Acknowledgements

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11.) R.C. Bossert, et. al., "Construction Experiences with SSC Collider Dipole Magnets at Fermilab", presented at the 12th International Conference on Magnet Technology, Leningrad, U.S.S.R., June 1991. Also see J. Strait, et. al., "Mechanical Behavior of Fermilab-Built 1.5m Model SSC Collider Dipoles", presented at the same conference.

12.) See ref. 10

13.) M. N. Wilson, *Superconducting Magnets*, New York: Oxford University Press, 1983.

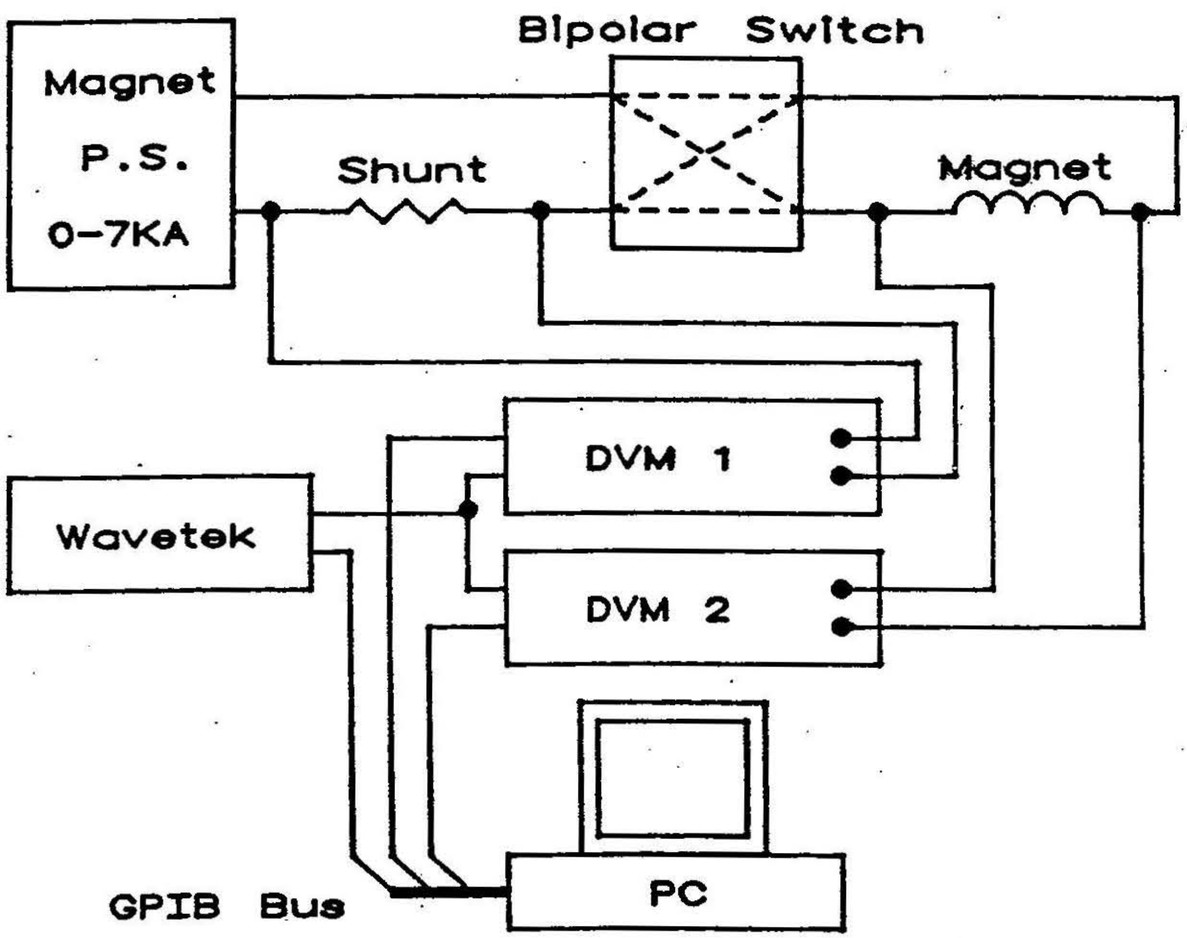

Bipolar Switch
Magnet
P.S.
0-7KA
Shunt
Magnet
DVM 1
Wavetek
DVM 2
PC
GPIB Bus

Figure 1

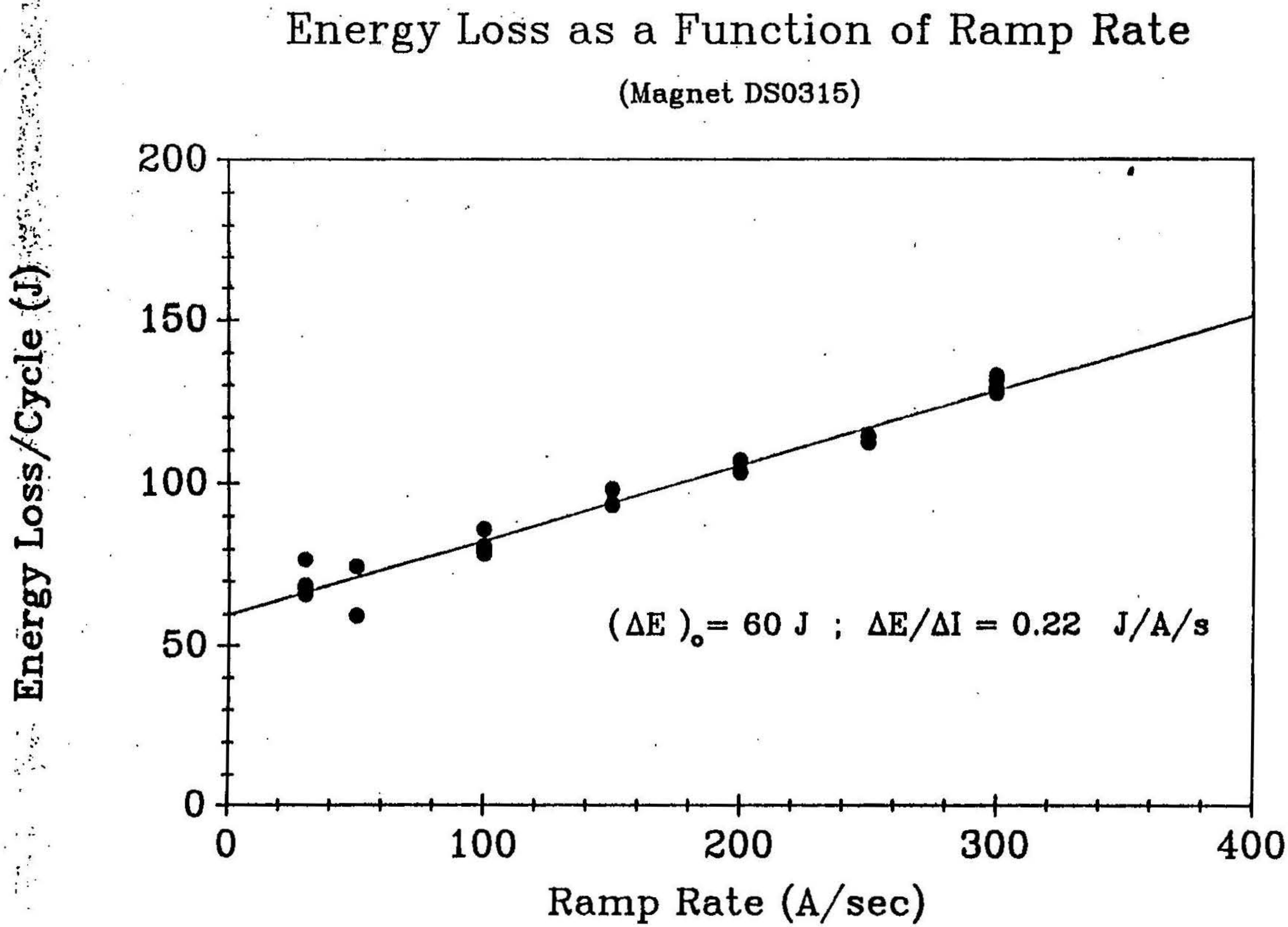

Energy Loss as a Function of Ramp Rate
(Magnet DS0315)
Energy Loss/Cycle (J)
Ramp Rate (A/sec)
$(\Delta E)_o$ = 60 J ; $\Delta E/\Delta I$ = 0.22 J/A/s
0
50
100
150
200
0
100
200
300
400

Figure 2

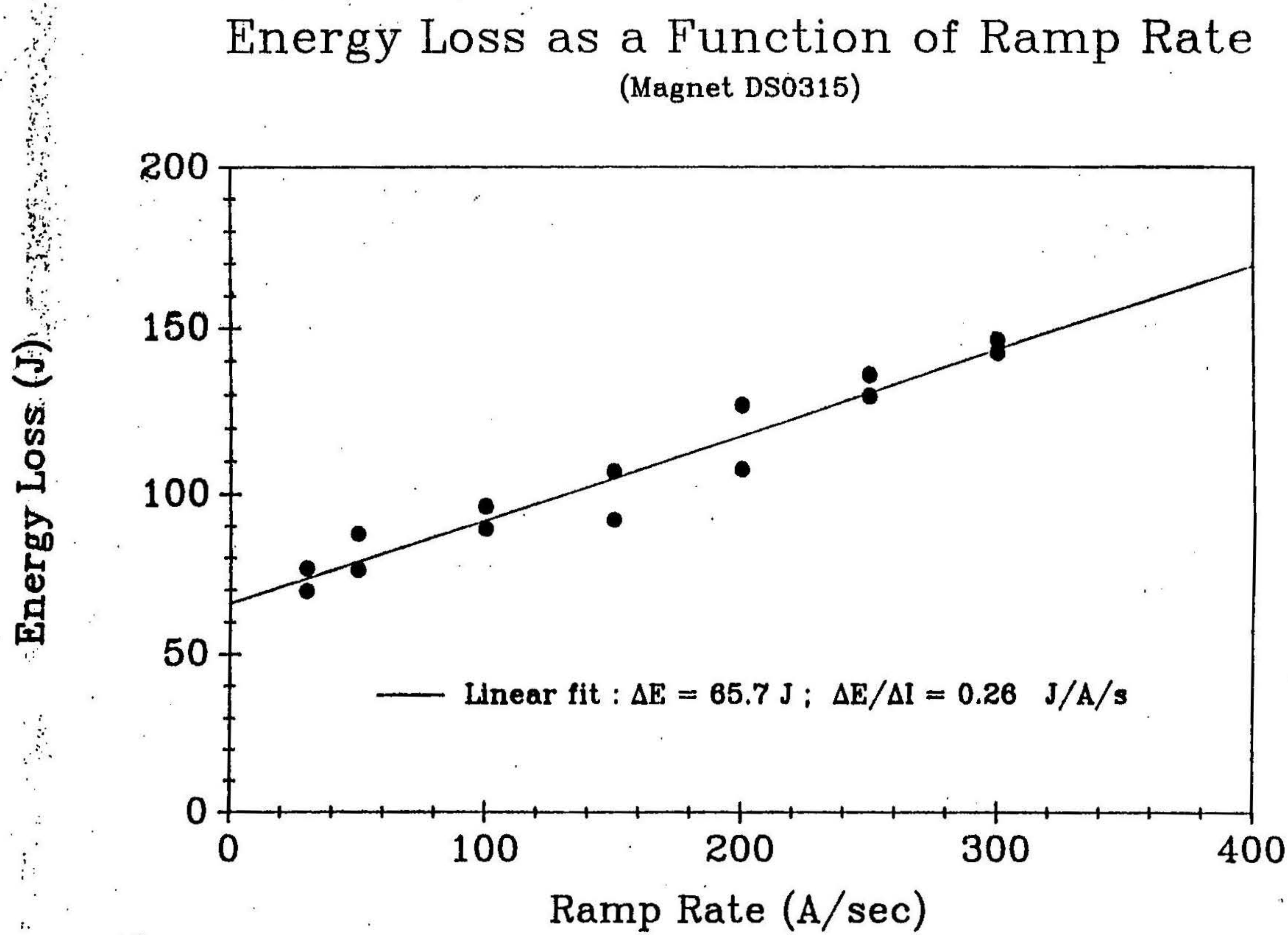
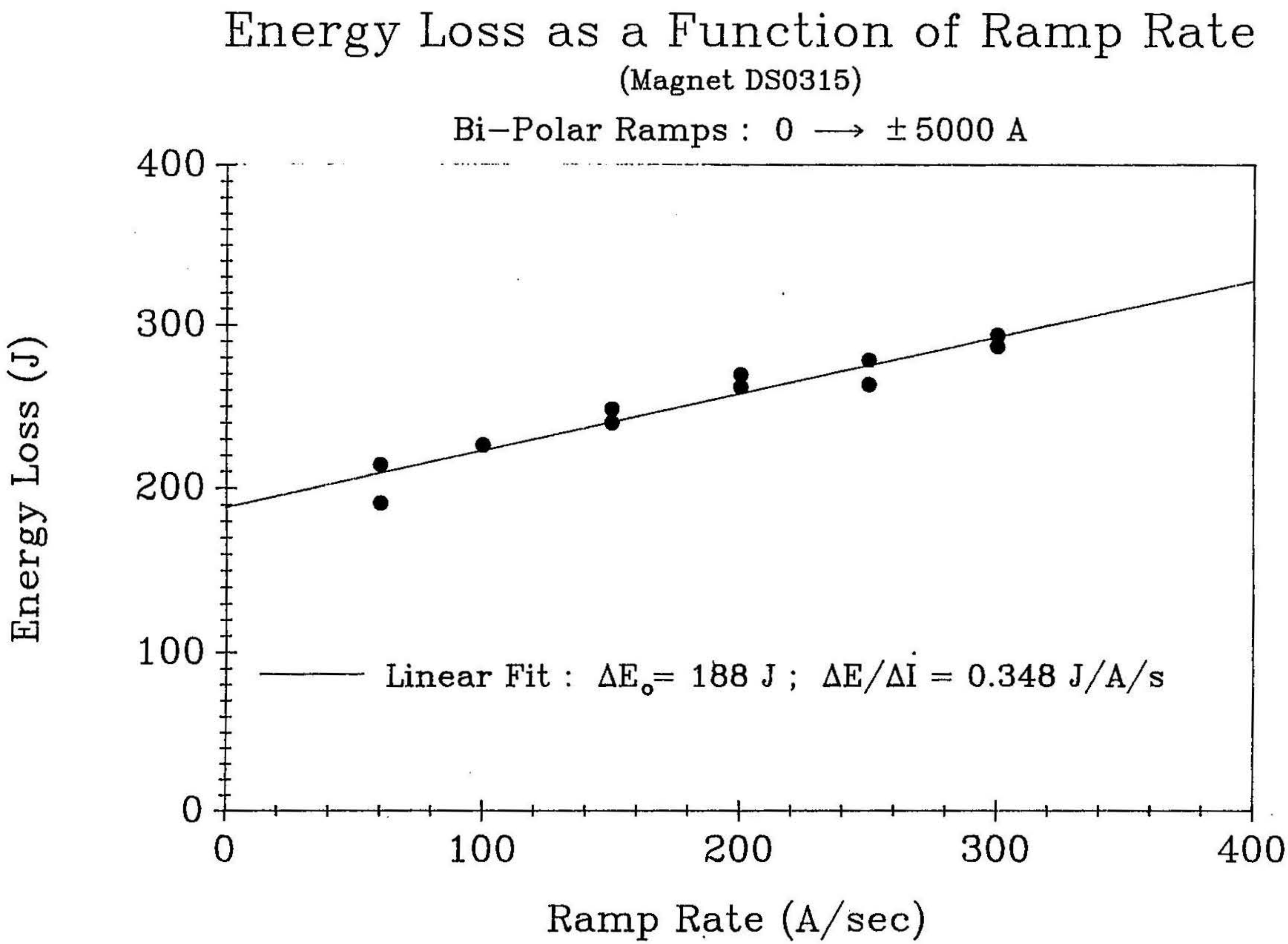
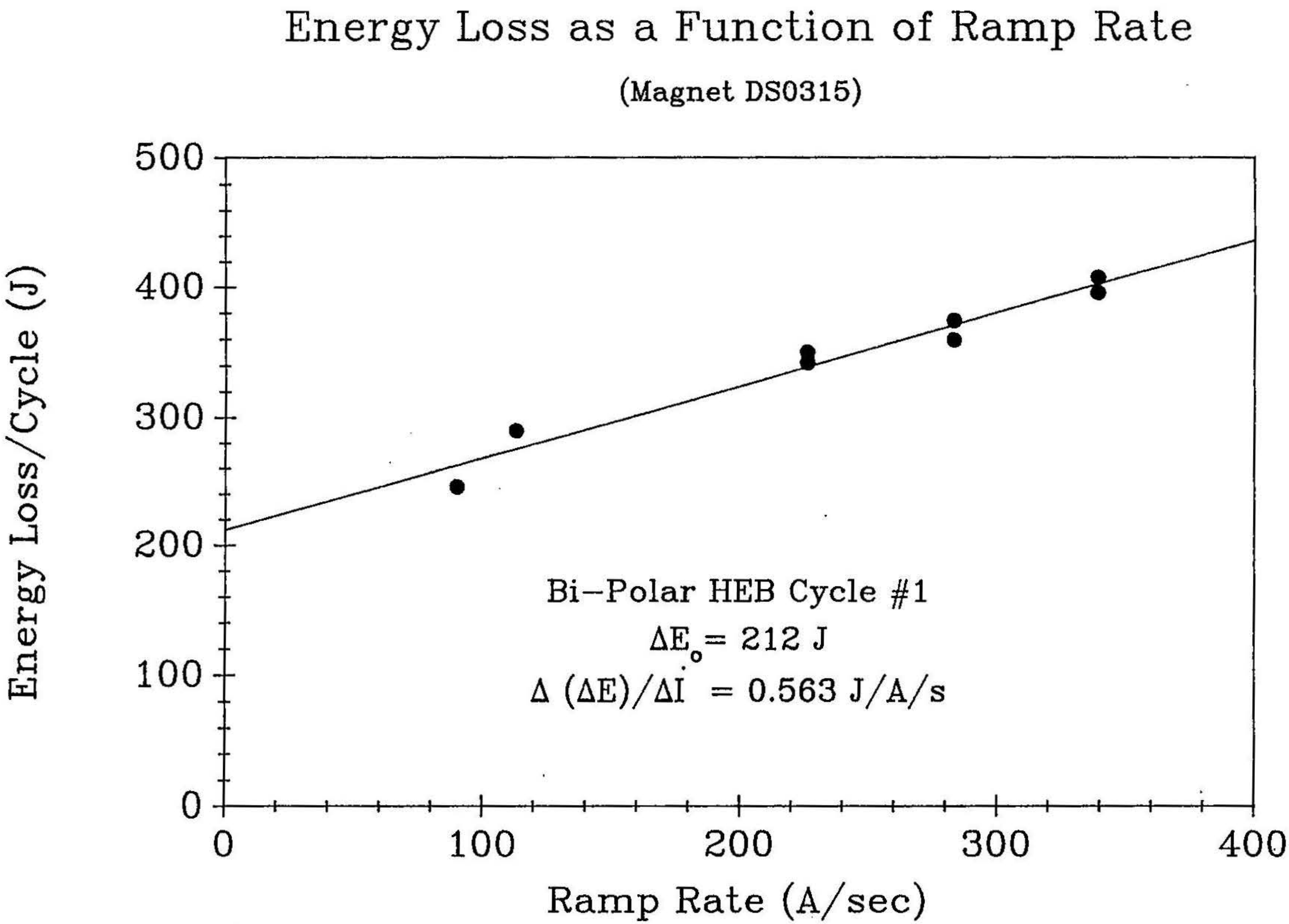

Energy Loss as a Function of Ramp Rate
(Magnet DS0315)
200
150
100
50
0
0
100
200
300
400
Energy Loss (J)
Ramp Rate (A/sec)
Linear fit : ΔE = 65.7 J ; ΔE/ΔI = 0.26 J/A/s

Figure 3



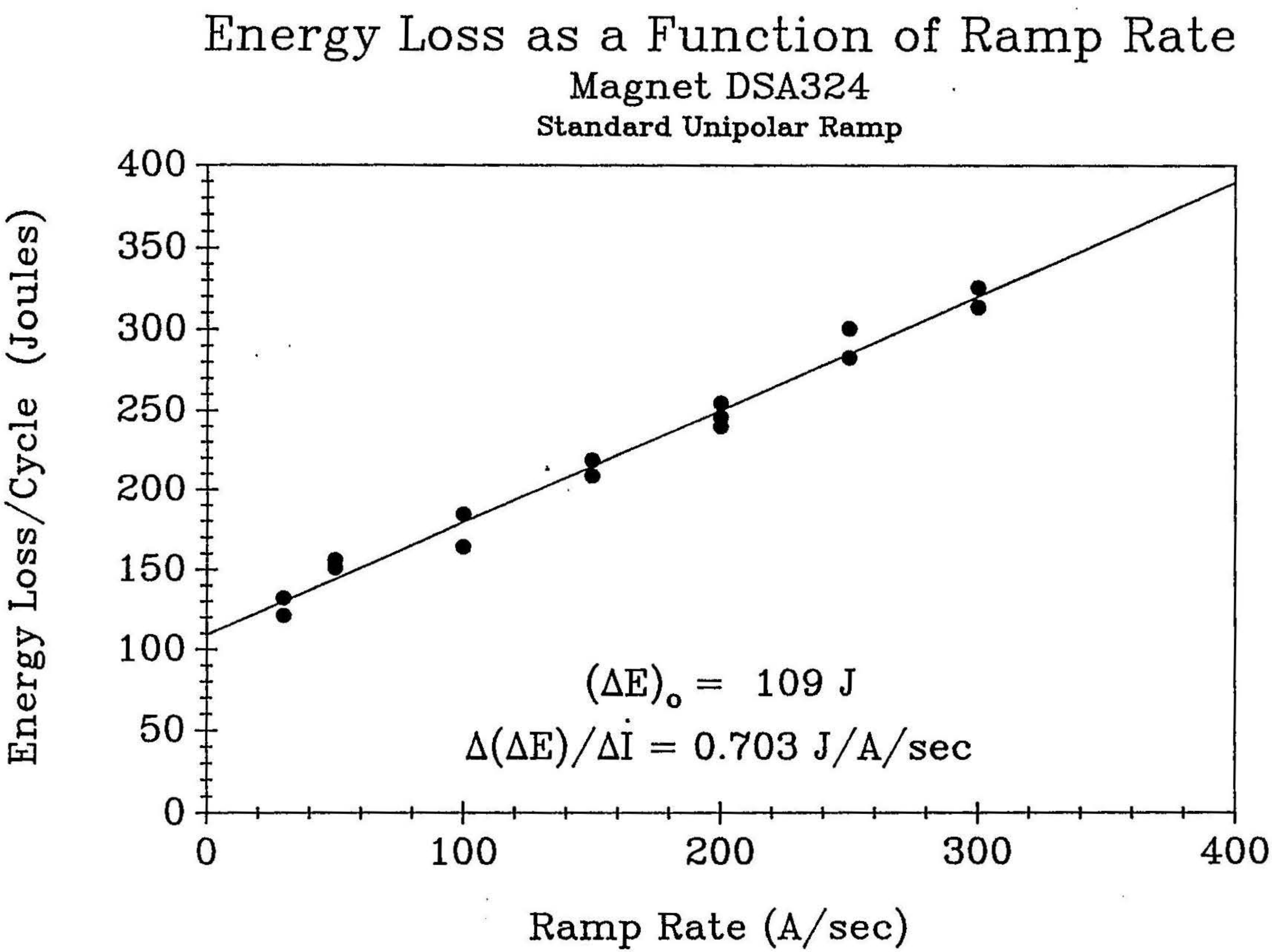
Energy Loss as a Function of Ramp Rate
(Magnet DS0315)
Bi-Polar Ramps : 0 ⟶ ±5000 A
400
300
200
100
0
Energy Loss (J)
0
100
200
300
400
Ramp Rate (A/sec)
Linear Fit : ΔE$_o$= 188 J ; ΔE/ΔI = 0.348 J/A/s

Figure 4



Energy Loss as a Function of Ramp Rate
(Magnet DS0315)
Energy Loss/Cycle (J)
500
400
300
200
100
0
0
100
200
300
400
Ramp Rate (A/sec)
Bi–Polar HEB Cycle #1
$\Delta E_o = 212$ J
$\Delta(\Delta E)/\Delta\dot{I} = 0.563$ J/A/s

Figure 5



Energy Loss as a Function of Ramp Rate
Magnet DSA324
Standard Unipolar Ramp
Energy Loss/Cycle (Joules)
0
50
100
150
200
250
300
350
400
(ΔE)o = 109 J
Δ(ΔE)/Δİ = 0.703 J/A/sec
0
100
200
300
400
Ramp Rate (A/sec)

Figure 6

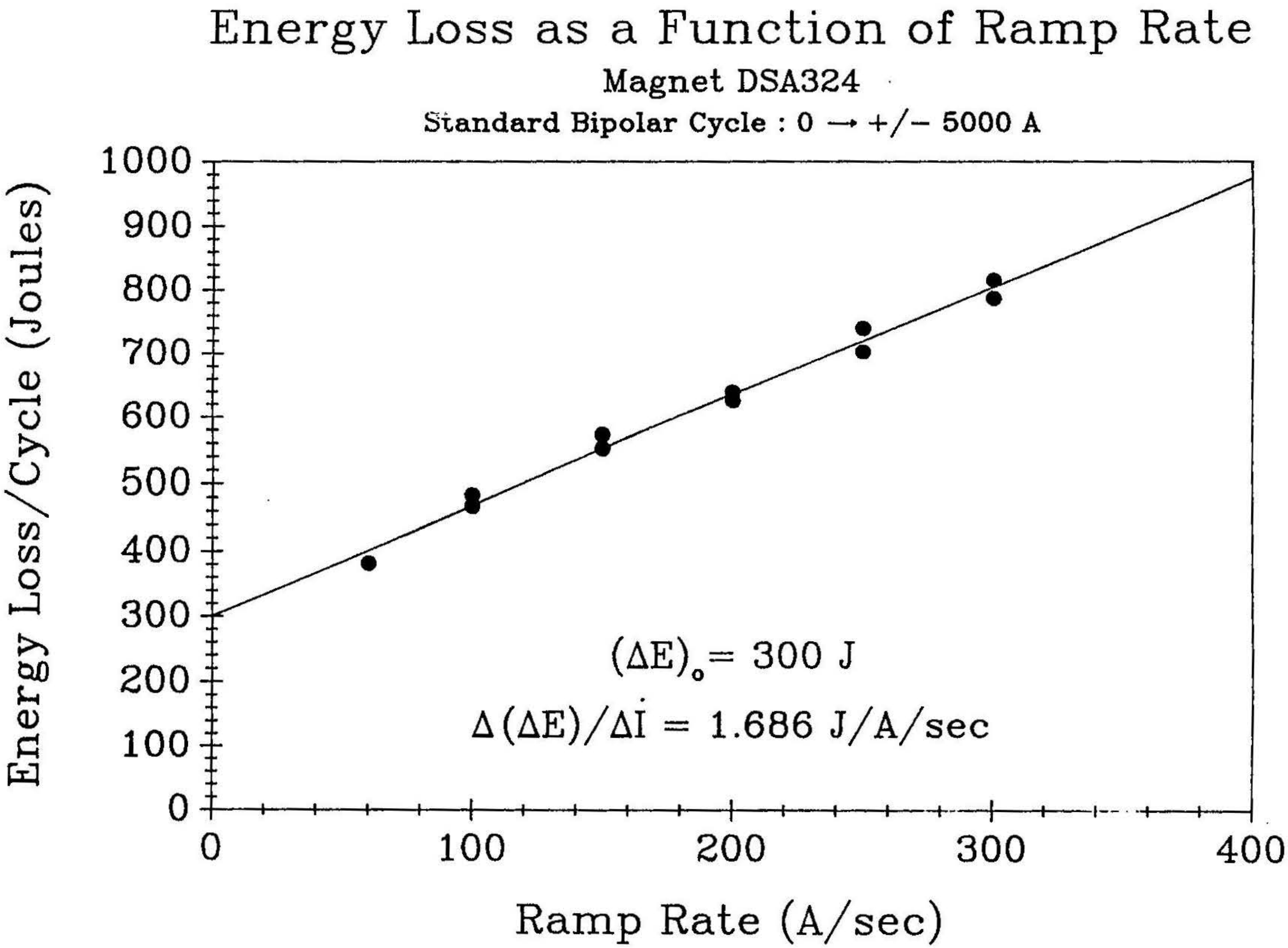
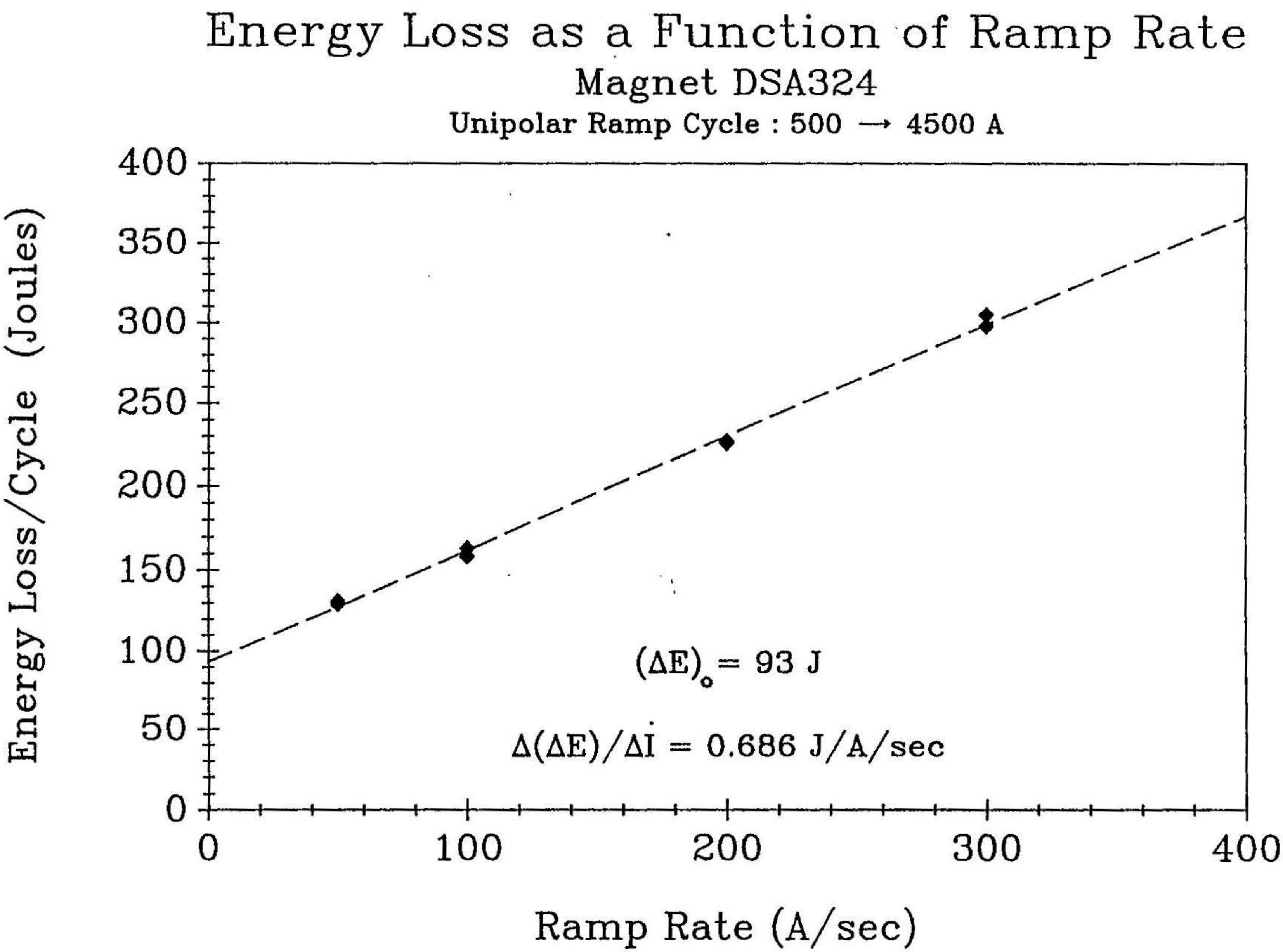

Energy Loss as a Function of Ramp Rate
Magnet DSA324
Standard Bipolar Cycle : 0 → +/− 5000 A
Energy Loss/Cycle (Joules)
1000
900
800
700
600
500
400
300
200
100
0
100
200
300
400
Ramp Rate (A/sec)
(ΔE)o = 300 J
Δ(ΔE)/Δİ = 1.686 J/A/sec

Figure 7



Energy Loss as a Function of Ramp Rate
Magnet DSA324
Unipolar Ramp Cycle : 500 → 4500 A
Energy Loss/Cycle (Joules)
Ramp Rate (A/sec)
(ΔE)o = 93 J
Δ(ΔE)/ΔI = 0.686 J/A/sec
0
50
100
150
200
250
300
350
400
0
100
200
300
400

Figure 8

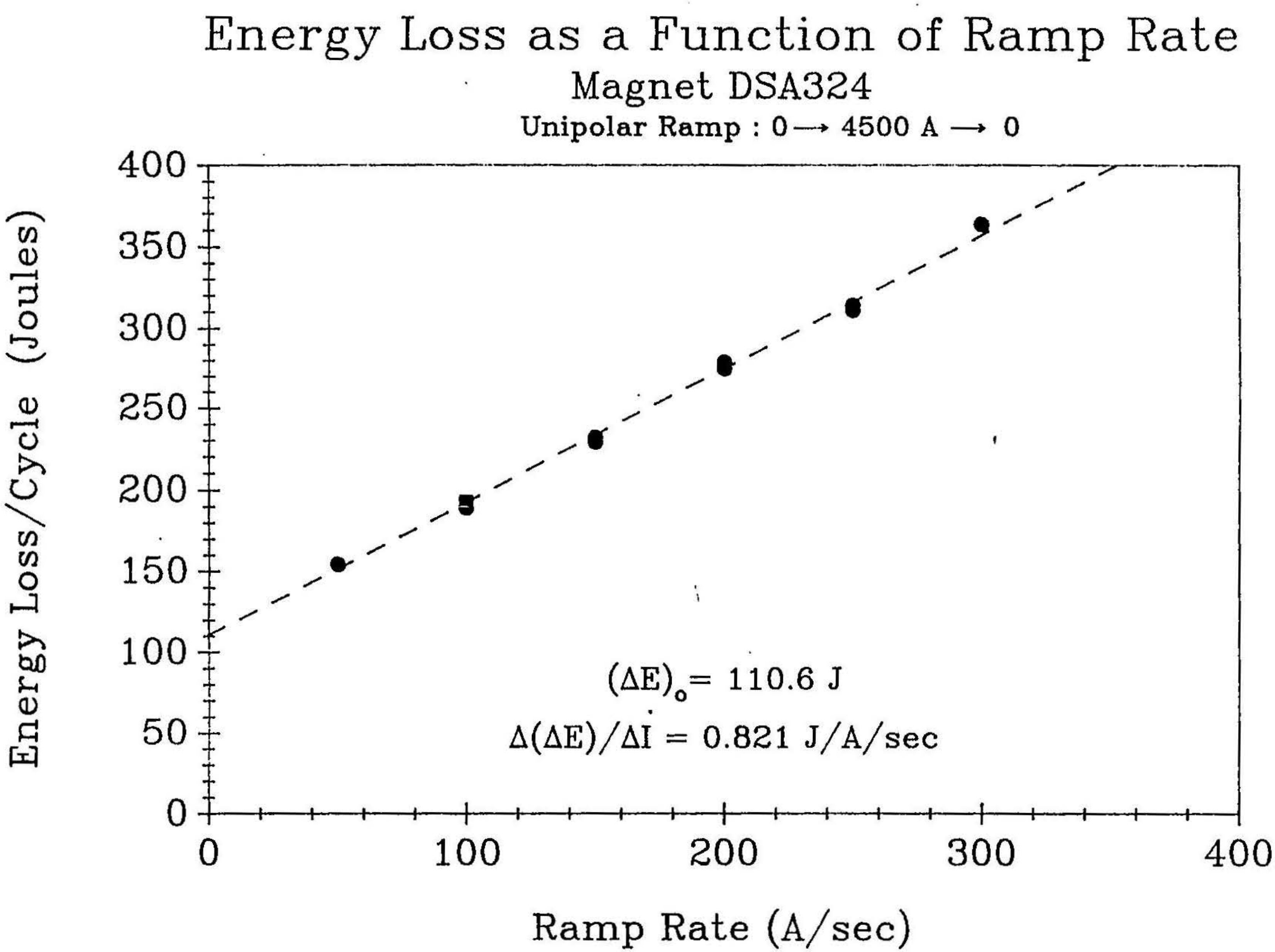

Energy Loss as a Function of Ramp Rate
Magnet DSA324
Unipolar Ramp : 0 ⟶ 4500 A ⟶ 0
Energy Loss/Cycle (Joules)
400
350
300
250
200
150
100
50
0
0
100
200
300
400
Ramp Rate (A/sec)
(ΔE)o = 110.6 J
Δ(ΔE)/ΔI = 0.821 J/A/sec

Figure 9

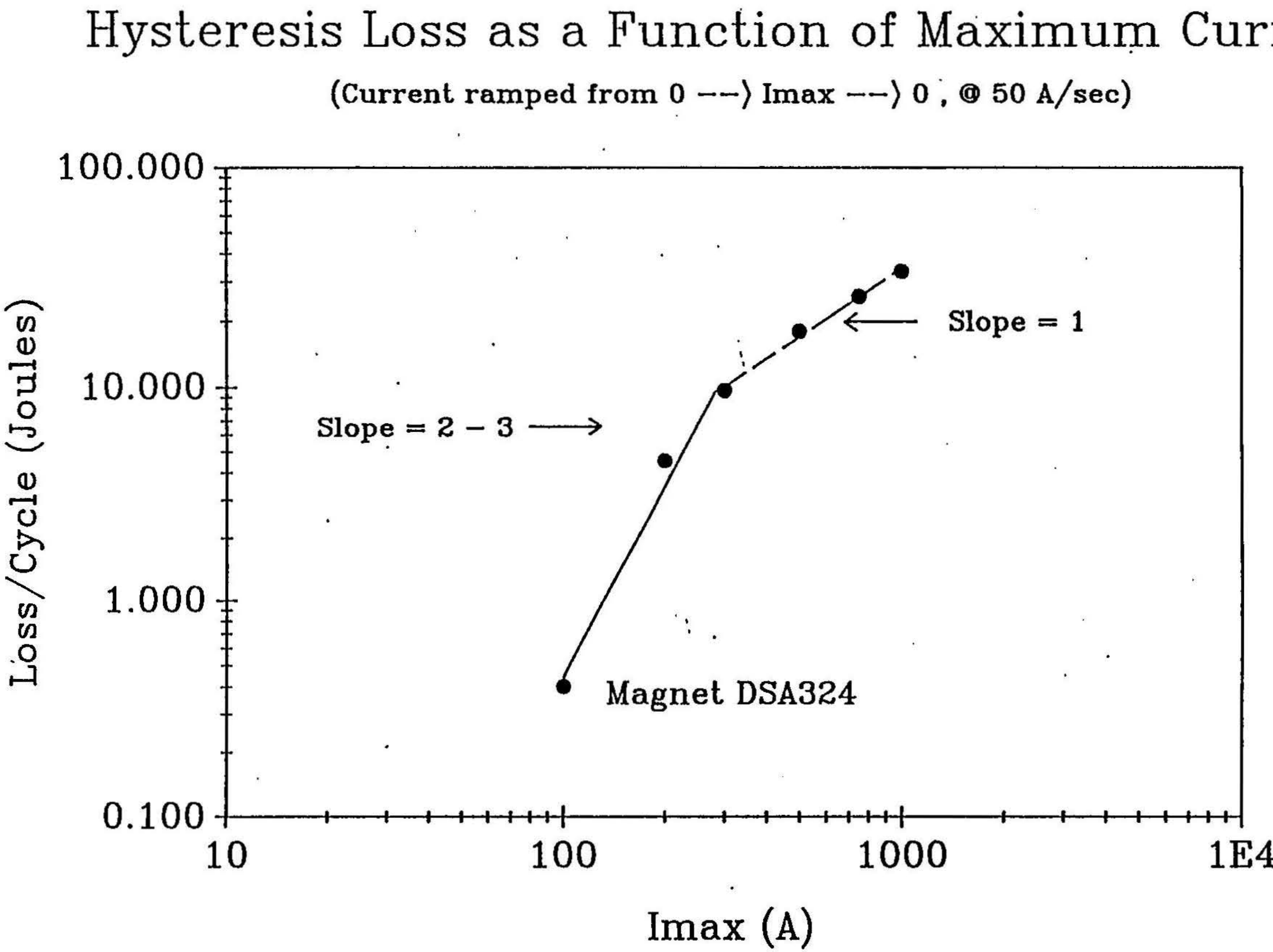

Hysteresis Loss as a Function of Maximum Current
(Current ramped from 0 --⟩ Imax --⟩ 0 , @ 50 A/sec)
100.000
10.000
1.000
0.100
Loss/Cycle (Joules)
Slope = 1
Slope = 2 – 3
Magnet DSA324
10
100
1000
1E4
Imax (A)

Figure 11

Distribution:

<u>FNAL</u>
S. Delchamps
W. Koska
M. Lamm
G. Pewitt
J. Strait
M. Wake
B. Williams

<u>SSCL</u>
R. Coombes
J. Jayakumar
G. Snitchler
J. Tompkins

<u>BNL</u>
P. Wanderer