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CORRECTIONS TO AC LOSS MEASUREMENTS IN LONG SSC COLLIDER DIPOLES DUE TO OBSERVED DC ENERGY DISSIPATION

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Introduction

AC loss measurements in long SSC collider dipoles have recently been performed[1]. As a matter of procedure, measurements are also taken for DC current levels, at 0 and 5000 Amps, in order to evaluate any steady-state contribution to the energy loss, which might result from fluctuations in the power supply, or electrical noise in the external environment. Previously, in short magnet measurements, we have found essentially no contribution at DC currents[2]. However, this has not been the case for the long magnets recently tested. While the measured loss at DC currents of 0 A has indeed remained zero, the loss at 5000 A (DC) has increased to a measurable amount. This indicates that there must be some power supply fluctuation (dI/dt) which produces a non-zero magnet voltage, which is not necessarily random, and therefore, does not identically integrate to zero. Effects of noise from the external electromagnetic environment (i.e., inductive or capacitive pick-up) are believed to be negligible, as they would contribute equally at 0 A (DC) and 5000 A (DC), whereas non-zero losses at DC currents are only observed when the power supply is at non-zero current, possibly arising from irregular power supply regulation.

Recent measurements of magnets DCA311 and DCA312 have indicated a substantial difference in the hysteresis loss during a standard unipolar ramp cycle between these two magnets. It has been suggested[3] that this difference may be attributable to some systematic error in the measurement process. One mechanism to be considered is that of contributions to the overall measured loss from the observed non-zero DC loss. In the following paper we discuss the methodology used in deriving a correction to the measured AC losses, and the resultant effects on the long magnet result, showing that the difference in hysteresis loss is most likely not due to DC energy dissipation.

Derivation of the Correction

Consider that we observe some non-zero energy loss for a DC current measurement, E'. (This loss is the integral of the product V*I with respect to time, evaluated over a certain time t_{dc}.) We can then write the power dissipated at this current as E'/t_{dc}. Under the assumption that this power is a linear function of the DC current, corresponding to a constant magnet voltage during a ramp cycle with some constant non-zero dI/dt, vanishing at I=0, we can write the power dissipated as :

$$P' = ((E'/t_{dc})/5000)((dI/dt * t) + 500) \qquad (1)$$

where E' is the loss measured at 5000 A (DC), t_{dc} is the time over which the DC measurement is made, dI/dt is the ramp rate for a given measurement, t is time, and 500 represents the DC offset of the standard unipolar ramps used in the AC loss measurements. We can then find the loss due to power supply fluctuations by integrating this expression for power with respect to time over the time for a complete current cycle, namely :

$$E_{ps} = ((E'/t_{dc})/5000) \int_0^{t_c} ((dI/dt)t + 500)dt \tag{2}$$

where the integral is evaluated over the cycle time t_c. Since dI/dt is discontinuous over a complete cycle, and the cycle is symmetric, we can re-write this expression to facilitate it's evaluation as :

$$E_{ps} = 2((E'/t_{dc})/5000) \int_0^{t_{1/2}} ((dI/dt)t + 500)dt \quad + \quad E'_{500} \quad + \quad E'_{5000} \tag{3}$$

where $t_{1/2}$ is the time for half a ramp cycle (minus the dwell times), and E'_{500} and E'_{5000} are the losses from the 5 second dwells at 500 and 5000 A, and are given by :

$$E'_{500} = (E'/t_{dc})\ (500/5000)*5 \tag{4}$$

and

$$E'_{5000} = (E'/t_{dc})*5 \tag{5}$$

Note that in this treatment, resistive losses at DC currents due to the small but finite splice resistances present in the cable have been neglected, for they can be shown to be on the order of only a few Joules, much less than the observed DC losses.

Using equations 3,4, and 5, we can then determine the correction to the AC loss measurements at each ramp rate studied. These corrections must then be subtracted from the measured values of the AC loss.

Corrections to Long Magnet Results

As the values for the energy loss at DC currents of 5000 Amps differ substantially for the two long magnets studied, the corrections will have to be calculated in each case. For magnet DCA311, we measured an average energy loss at 5000 A (DC) of 63 Joules over a time period of 133.33 seconds. This corresponds to a power of 0.47 Watts. In the case of magnet DCA312, the DC loss over the same length of time was 123.5 Joules, leading to a power of 0.93 Watts. These values for the power dissipated at a DC current of 5000 A are to be used in expressions 3,4, and 5 above, in place of (E'/t_{dc}). We also need the half-cycle time for the various ramp cycles; this is shown in Table I below :

Table I

Ramp Rate (A/sec)	$t_{1/2}$ (sec)
30	150
40	112.5
50	90
60	75
75	60
90	50
100	45
125	36
150	30

Using these values for $t_{1/2}$, and the DC power, we can then find the corrections to the AC loss measurements. These are summarized in Table II as follows :

Table II

Magnet DCA311

Ramp Rate (A/sec)	Energy Correction (J)	Uncorrected Loss (J)	Corrected Loss (J)	Correction as %
30	81	1499	1418	5.4
"	"	1105	1024	7.9
50	49	1334	1285	3.7
"	"	1262	1213	3.9
75	34	1695	1661	2.0
"	"	1450	1416	2.4
100	26	2186	2160	1.2
"	"	2184	2158	1.2
125	21	2625	2604	0.8
150	18	3072	3054	0.6
	"	3031	3013	0.6

Magnet DCA312

Ramp Rate (A/sec)	Energy Correction (J)	Uncorrected Loss (J)	Corrected Loss (J)	Correction as %
30	192	3678	3486	5.2
"	"	3150	2958	6.1
40	145	3256	3111	4.5
"	"	3535	3390	4.1
50	117	4012	3895	2.9

"	"	4008	3891	2.9
60	99	4481	4382	2.2
"	"	4626	4527	2.1
75	80	5586	5506	1.4
"	"	5531	5451	1.5
90	68	6652	6584	1.0
"	"	6427	6359	1.1

As is evident from this table, the correction, as a percentage of the uncorrected value, is never greater than 8 %, and is in general less than our measurement uncertainty. It also decreases quickly with higher ramp rates, as we would expect, since shorter cycle times imply less integrated energy loss for a monotonically increasing relationship between power and current.

We have plotted the ramp rate dependance of these two magnets in Figures 1 and 2, using the corrected values. Note that the calculated values of the hysteresis loss and ramp rate dependance have now changed somewhat. These parameters are summarized in Table III :

Table III

Magnet	Hysteresis Loss (uncorrected) (J)	Hysteresis Loss (corrected) (J)	Ramp Rate Dep. (uncorrected) (J/A/sec)	Ramp Rate Dep. (corrected) (J/A/sec)
DCA311	614	534	15.7	16.2
DCA312	1393	1164	55.4	57.4

In general we see that the hysteresis losses have decreased in both cases, by between 13 and 16 %, while the eddy current loss has increased by 3- 4 %.

Conclusions

We have shown that the contribution to the measured AC losses of long magnets due to energy dissipation in the magnet under DC conditions (possibly arising from power supply ripple) can in some cases be non-negligible. We find, however, that except in the case of the lowest ramp rates, the correction is on the order of the measurement uncertainty (as defined by the standard deviation of a set of measurements). This DC dissipation can not account for the difference between the surprisingly large hysteresis losses observed in magnet DCA312 and the smaller losses observed in magnet DCA311. From simple scaling arguments, however, the hysteresis loss of magnet DCA312 would appear to be reasonable, as the ratio of the hysteresis loss in magnet DCA312 to that of magnet DSA324 (short 50mm magnet) is 10.7, in good agreement with the ratio of the coil lengths (11.7). The ratio of eddy current losses, however, is about 80, roughly 7 times as high as expected from scaling by coil length, indicating, perhaps, differences in intra-strand resistance between the cables used in these two magnets, and, indeed, between magnets DCA311 and DCA312.

References

1.) "Measurements of AC Losses in Long 50mm SSC Collider Dipole Magnets at Fermilab", J. Ozelis, Fermilab TS-SSC-91-249

2.) "AC Loss Measurements in Model Magnets at Fermilab", J. Ozelis, MSI Meeting 5/14/91, Fermilab. Also Fermilab TS-SSC-91-190

3.) M. Wake, Private communication

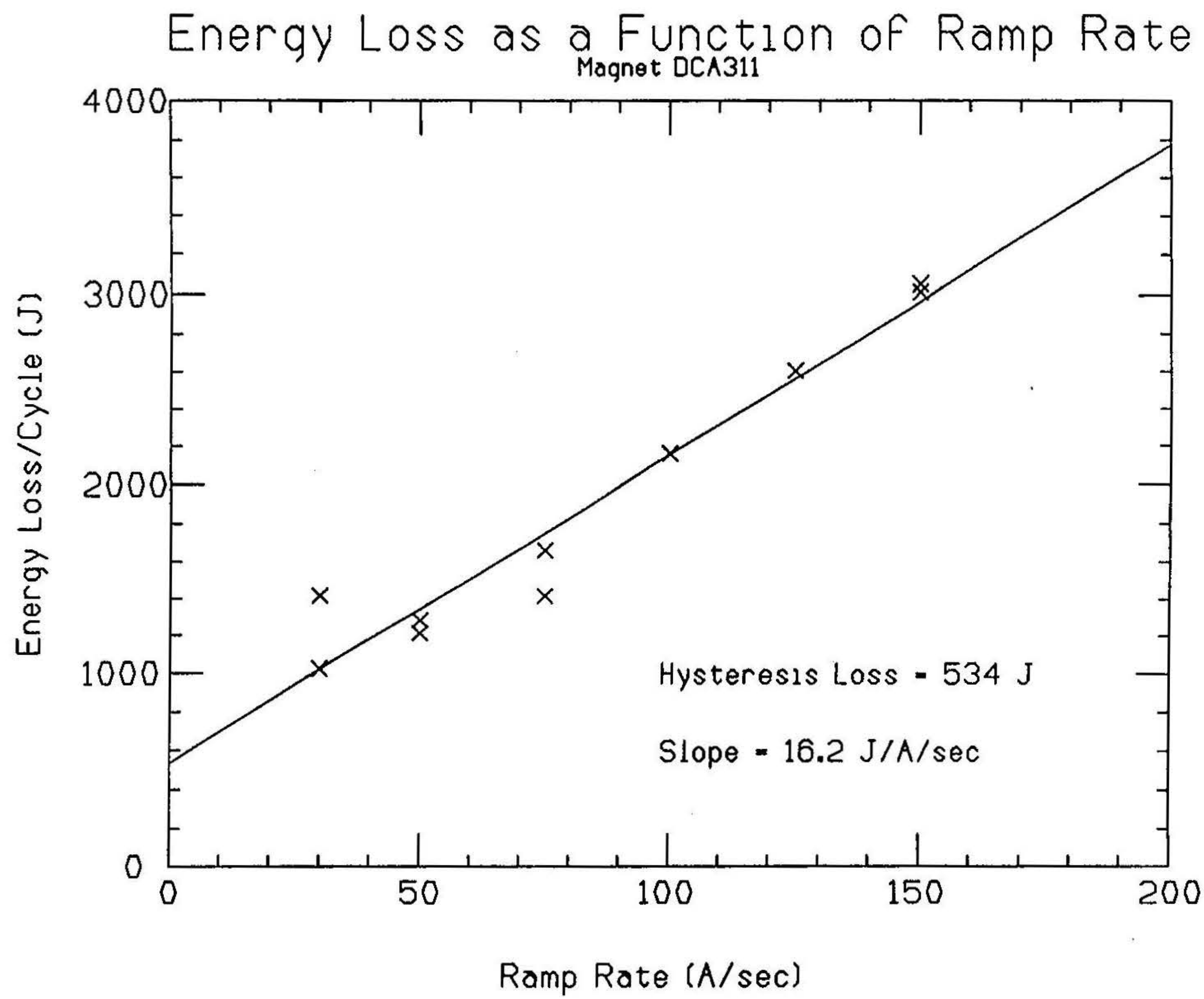
Energy Loss as a Function of Ramp Rate
Magnet DCA311
Energy Loss/Cycle (J)
4000
3000
2000
1000
0
0
50
100
150
200
Ramp Rate (A/sec)
Hysteresis Loss = 534 J
Slope = 16.2 J/A/sec

Figure 1

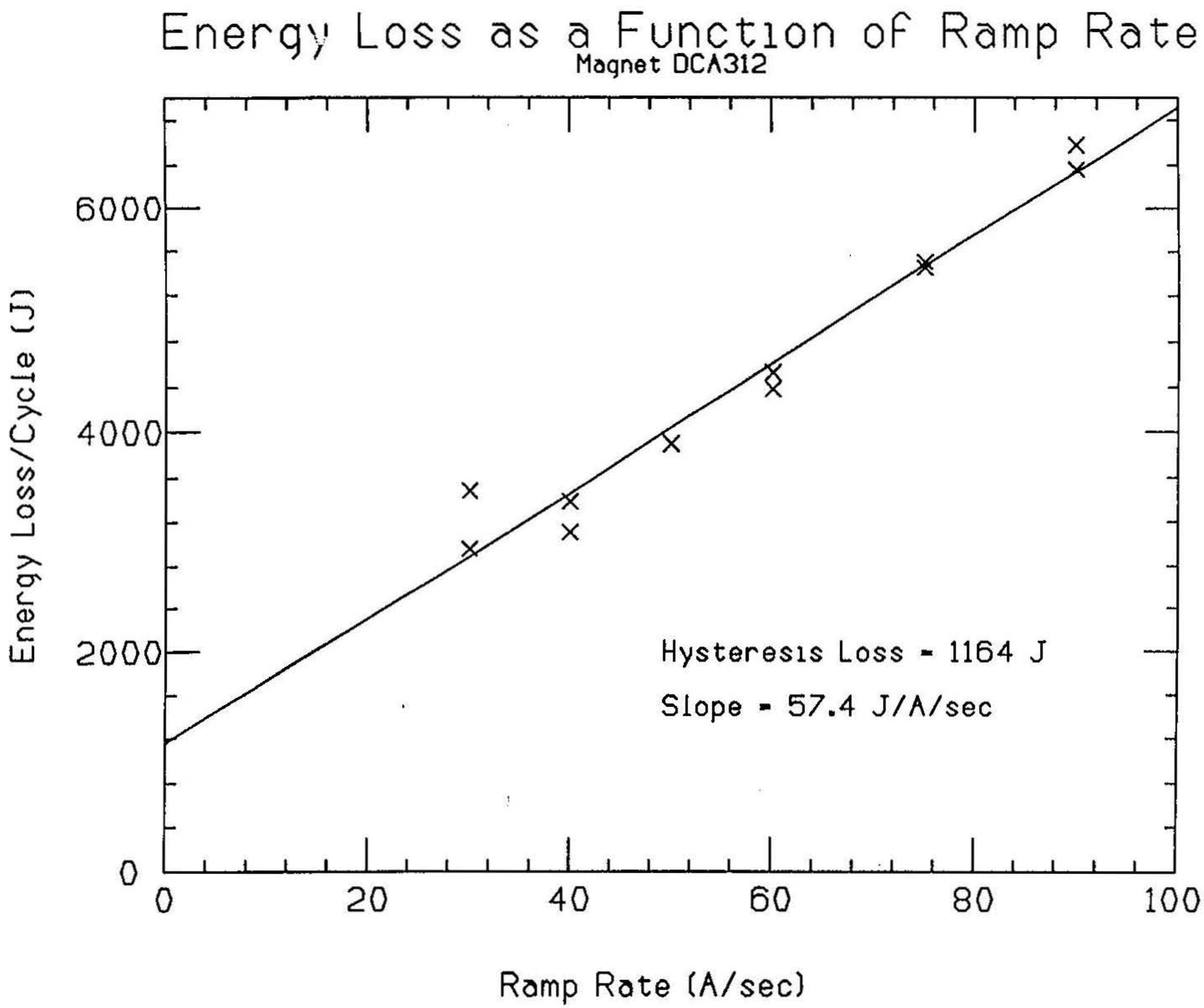
Energy Loss as a Function of Ramp Rate
Magnet DCA312
Energy Loss/Cycle (J)
Ramp Rate (A/sec)
Hysteresis Loss = 1164 J
Slope = 57.4 J/A/sec
0
2000
4000
6000
0
20
40
60
80
100

Figure 2