Fermi National Accelerator Laboratory

FERMILAB-Conf-92/238

AC Loss Measurement of SSC Dipole Magnets

M. Wake, S. Delchamps, R. Hanft, T. Jaffery, W. Kinney, W. Koska,
M.J. Lamm, P.O. Mazur, D. Orris, J.P. Ozelis, J. Strait

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

September 1992

Presented at the *ICFA Workshop on AC Superconductivity (ACSC92)*
Tsukuba, Japan, June 22-25, 1992

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

AC Loss Measurement of SSC Dipole Magnets *

S. Delchamps, R. Hanft, T. Jaffery, W. Kinney, W. Koska, M. J. Lamm,
P. O. Mazur, D. Orris, J. P. Ozelis, J. Strait and M. Wake†
Fermi National Accelerator Laboratory, Batavia, IL. 60510 U.S.A

Abstract

AC losses in full length and 1.5 m model SSC collider dipoles were successfully measured by the direct observation of energy flow into and out of magnets during a ramp cycle. The measurement was performed by using two double-integrating type digital volt meters (DVM's) for current and voltage measurement. Measurements were performed for six 15 m long ASST magnets[1] and five 1.5 m long model magnets[2], including one 40 mm diameter magnet. There were large variations in the eddy current losses. Since these magnets use conductors with slight deviations in their internal structures and processing of the copper surface depending on the manufacturer, it is likely that there are differences in the contact resistance between strands. Correlation between the ramp rate dependence of the quench current and the eddy current loss was evident.

1 INTRODUCTION

A superconducting magnet, which has zero resistance under DC operation, dissipates energy when the transport current is ramped. This energy dissipation results from magnetization hysteresis due to the pinning of the fluxoids in the superconductor. In practical magnets, eddy current losses due to the coupling between filaments in a strand as well as the coupling between strands through the contact resistances between strands in a cable also contribute to the measured loss. Domain motion hysteresis in the ferromagnetic iron yoke also causes a hysteresis loss. Eddy current losses depend on ramp rate while the pinning loss and iron loss per cycle are ramp rate independent. Since AC losses cause a temperature rise in the magnet, it is important to measure the AC loss of magnets to ensure the proper operation of the magnet under AC ramp conditions. In the SSC project, this measurement is especially important for fast ramp magnets such as High Energy Booster (HEB) magnets.

*Work supported by U.S. Department of Energy †On leave from KEK National Laboratory for High Energy Physics

Recent observations of the ramp rate dependence[3] of quench current in SSC collider dipoles also reinforce the need for reliable AC loss measurements of these magnets.

In the past, various measurement techniques have been applied to the loss measurement of superconducting magnets. Calorimetric methods using boil off of the liquid helium [4] were used with the disadvantage of a long system time constant, leading to measurement inaccuracy. Calorimetric methods using temperature controlled feedback of a superfluid bath improved the accuracy of this type of measurement[5]. Electronic methods using analog integrators were also widely used[6][7], requiring careful adjustment to eliminate drift of the integrator. Digital integration with a bucking coil to subtract the inductive component of the magnet voltage was used in AC loss measurements of Tevatron magnets[8]. Electrical methods usually suffer inaccuracies arising from magnet power supply noise. However, through proper handling of the signal, these methods can provide the most accurate measurement of AC loss. The measurement reported in this paper uses a totally digital system of a small computer equipped with fast and accurate DVM's. This direct method requires no calibration or adjustment in the measurement.

2 MEASUREMENT SYSTEM

Energy losses are observed as the difference between the energy injected into and extracted from the magnet. The integration of $I \times V$ throughout a ramp cycle should represent this loss of energy. The primary task required of the hardware system is to take accurate, synchronous voltage and current measurements. For these measurements, the magnet voltage was measured using an HP Model 3457A DVM. The magnet current was determined using a previously calibrated 12kA shunt for 1.5 m model magnets, and from a Holec transducer signal for 15 m magnets. The current signal was likewise measured using an HP Model 3457A DVM. The DVM's were controlled via a GPIB bus using a PC and a data acquisition program written in the ASYST programming environment. Since the total energy flow into and out of the magnet is very large compared to the energy dissipated in the magnet, slight relative timing errors between the current and voltage can cause a large measurement error. Simultaneous triggering of the current and voltage DVM's is therefore essential. The DVM's were synchronously triggered using a Wavetek Model 75 digital waveform generator, which provided a train of squre waves as trigger signals. The number of pulses in the train was determined by the number of readings needed to capture a complete ramp cycle.

One of the most efficient ways to reduce noise in an environment where large power line cycle noise is dominant is through the integration of the signal for an integer number of line cycles. The DVM's were configured to integrate individual voltage readings for a period of 10 power-line cycles (0.167 sec), and individual readings were stored in internal memory, to be read out in FIFO mode by the PC. Readings were taken at a frequency of 4.5 Hz (every 0.222 sec).

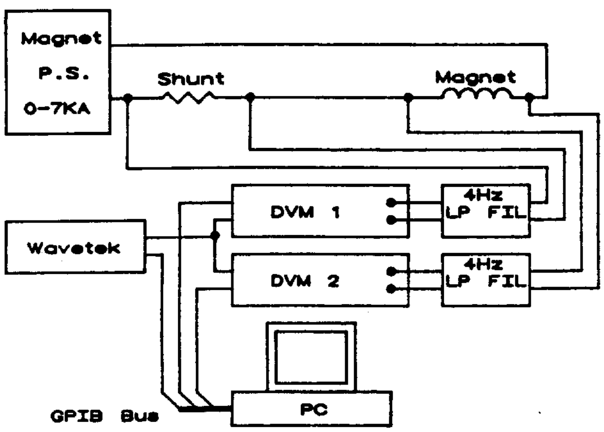

Fig.1 Measurement System

The DVM's had an inherent dead time of 56 msec for each measurement, corresponding to the maximum discharge period of an integrating capacitor. The incidence of magnetization change occurs at the edge of the current sweep, where the ramp rate is not constant. The duration of this edge is about 100 msec. Therefore, a 4.5 Hz measurement rate with a dead time of 56 msec is not sufficient to follow the process with adequate resolution. The addition of a passive filter of time constant about the same as the dead time provides some sensitivity to the input voltage during the dead time. Such a filter also eliminates short duration voltage spikes due to the SCR firing pattern of the Transrex power supply. For both of these reasons, a 4Hz (time constant 0.0398 sec) low-pass filter was applied to both the current and voltage signals at the DVM's. The time constants of these filters were carefully adjusted to be identical, eliminating any possible contribution to the systematic error of the measurement. The range settings of the two DVM's have to be the same, to ensure that the magnet voltage and current signals are terminated with the same impedance at the DVM inputs. Thermal emf's and other irregular voltages should be avoided. Signal to noise ratio of the magnet voltage and current signals can be optimized through careful shielding and isolation of the signal cables. Figure 1 indicates the measurement system and components.

3 EVALUATION METHOD

The integration of $I \times V$ must be accomplished with a finite number of data points in an actual measurement. One of the possible sources of large systematic error is incomplete integration over the ramp cycle. The loss measurement should be carried out through an entire ramp cycle, but if the cycle is incomplete or the endpoints of the integration are chosen incorrectly, the difference between the stored energies at these points will be reflected as an additional contribution to the measured energy loss. For example, in the case of a full length SSC collider dipole, if the starting current and the ending current differ by 1A, 75J of stored energy is mistakenly counted as a contribution to the energy loss. With noise present, it is difficult to determine whether this incompleteness or endpoint uncertainty is real, or is an artifact of noise in the signals.

A good completeness check for a cycle is provided by:

$$\oint V dt = 0 \tag{1}$$

To reduce the inaccuracy due to incompleteness of the integration cycle, it is desirable to subtract the inductive part of the voltage before integration so that the subtraction of two large numbers (and concomitant numerical errors) can be avoided. The energy loss U is calculated by

$$\begin{aligned} U &= \oint I(t)V(t)dt \\ &= I(0)\oint V(t)dt - \oint \int_0^t V(t)dt \frac{dI}{dt} dt \\ &= -\oint [\int_0^t V(t)dt - LI(t) + LI(0)] dI \end{aligned} \tag{2}$$

where L is the inductance of the magnet, which changes with current due to iron saturation. For a full length SSC collider dipole magnet, we have

$$L = L_0[1 - 0.06\left(\frac{I}{5000}\right)^7] \quad (3)$$

This integration technique is identical to that used in the analog integrator method[6] except that it is performed digitally by a computer. A correction offset was addded to the measured voltage signal before the integration so that equation (1) was satisfied. This eliminated any systematic shift in the voltage as well as errors made in the determination of the ramp cycle endpoints.

4 MEASUREMENT RESULTS

Measurements were first attempted in 1.5 m model magnets. Data were taken on the 4th and 6th cycles of a series of (typically) 10 ramp cycles. These ramps were executed for various ramp rates, ranging from 30 A/sec to 300 A/sec. The standard current cycle was essentially a trapezoidal ramp from 500 to 5000 to 500 Amps, with 5 second dwells at the maximum and minimum currents. The energy loss per cycle for 1.5 m model magnets is plotted in Figure 2 as a function of ramp rate. The plot shows that the loss is essentially linearly dependent upon ramp rate, with a slope ranging from 0.25 to 0.75 J/A/sec. The slopes represent losses due to eddy currents. Such losses depend on the inter filament and inter strand couplings.

The intercept, which corresponds to the AC loss due to superconductor hysteresis and iron domain motion, is about 100 J for all 50mm magnets.

Magnet Number	Cable in/out	L_0 (mH)	Eddy Loss J/(A/sec)	Hysteresis Loss (J)
DS0315	-	3.90	0.25	53.
DSA323	S/I	6.78	0.62	96.
DSA324	S/I	6.78	0.75	92.
DSA328	S/I	6.78	0.63	100.
DSA329	S/I	6.78	0.63	97.
DCA311	S/I	75.9	12.0	744.
DCA312	I/I	75.9	63.0	739.
DCA314	I/I	75.9	35.7	759.
DCA315	I/I	75.9	49.7	769.
DCA318	O/K	75.9	7.46	723.
DCA319	O/O	75.9	9.36	713.

Table I. AC Loss Summary

DS0315 is a 40mm i.d. magnet. DCA series are full size 15m magnets. Others are 1.5 m models. S: Supercon, I: IGC, O: Oxford, K: Outokumpu

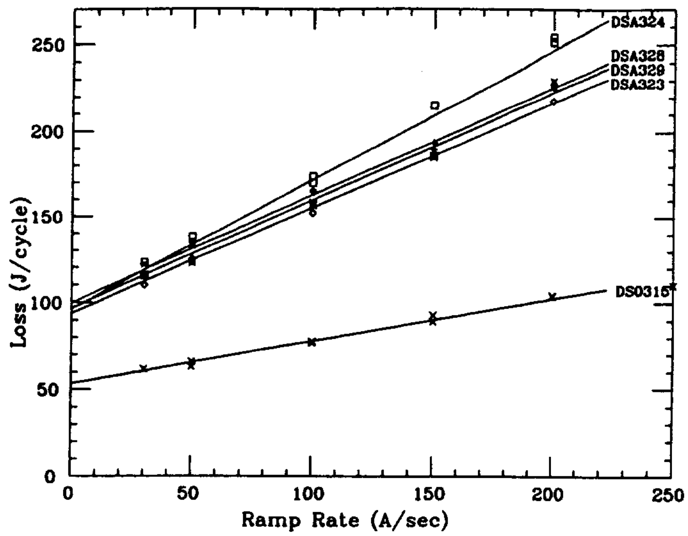

Fig.2 Short Magnet AC Loss

This type of loss is dependent primarily upon the nature of the superconducting cable, the magnet cross section, and the maximum field (current) change. It is therefore reasonable that a set of magnets with the same design should yield a similar value for the hysteresis loss. The 40 mm magnet had smaller losses, scaling with the volume of superconductor, which can be roughly estimated by comparing the inductances of the 40 mm and 50 mm magnets.

The reproducibility of these measurements is typically about 3% at present. Bipolar tests of a model magnet, simulating HEB operation, were performed as well[2]. Measurements were performed in an identical manner for the 15 m magnets that were part of the ASST magnet production program[1]. The results are shown in Figure 3. The hysteresis loss is about 750 J /cycle for all magnets in the series. However, this loss cannot be obtained by scaling up the model magnet result by the relative volume of superconductor. The eddy current losses show large variations from magnet to magnet. However, similar eddy current losses are observed in magnets containing cable from the same manufacturer. This makes sense if the strand to strand coupling varies between manufacturers. The strand to strand contact resistance should depend on the surface oxidation condition of the strands which may differ as a result of different manufacturing processes. The IGC strands used in magnets exhibiting high eddy current losses have undergone ultra clean surface treatment, and they should therefore have lower strand to strand resistences. Magnets with small eddy current losses showed an apparent nonlinear dependence of the AC loss with ramp rate at high ramp rates.

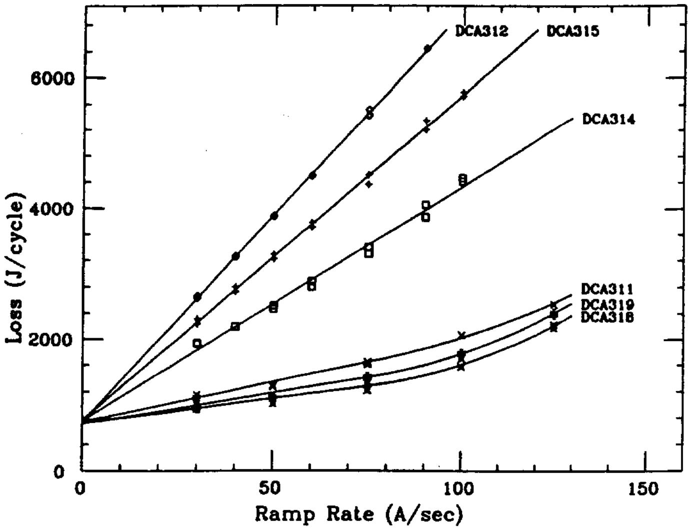

Fig.3 Long Magnet AC Loss

This could be due to a systematic error in the measurement. For example, sytematic errors due to mistiming will be larger at higher ramp rates. However, this nonlinearity does not appear in magnets showing large eddy current losses. More interesting possibilities are the nonlinear V-I characteristics of semiconducting copper oxide or an aparent magnetization due to the trapped persistent current.

The measured AC loss results are summarized in Table I.

5 EFFECT ON QUENCH BEHAVIOR

Since the AC loss of the magnet causes a concurrent temperature rise in the magnet, the quench current can be directly affected by the heat generated as a result of AC losses. Although SSC collider dipole magnets are going to be operated at slow ramp rates (typically 4A/sec), quench testing at high ramp rates was also performed and reported[3]. Fig 4 shows the relationship between eddy current loss and the quench current degradation due to high ramp rate. The relationship between quench current and AC loss is evident in the DCA series (full length) SSC dipole magnets.

6 CONCLUSION

AC loss measurements of SSC dipole magnets were performed using a completely digital method [1]. The results were more reliable than those yielded by previous techniques. At high ramp rates the quench current was seen to be affected by eddy current losses. This result is quite important for the development of SSC HEB magnets as well as for the further understanding of the behavior of SSC collider dipoles.

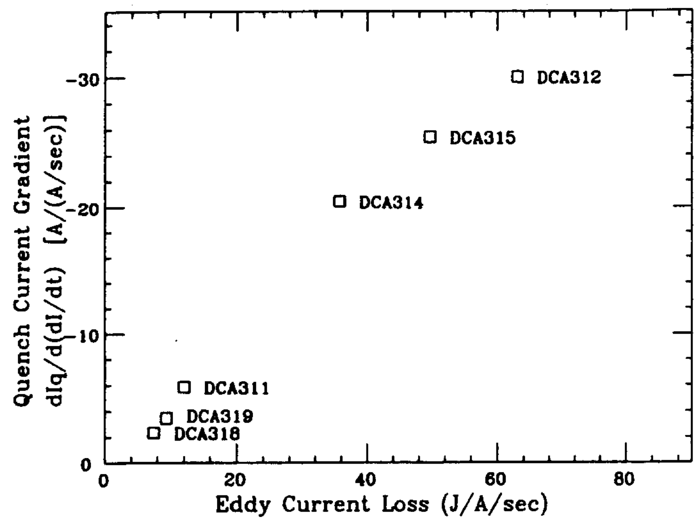

Fig.4 Quench Current vs. Eddy Current Loss

[1] The authors would like to thank to the Fermilab MTF and LAB2 staff for the operation of the cryogenic system and support of the measurement.

7 REFERENCES

[1] M.J.Blessing,*et al.* "Construction Experience with Fermilab-Built Full-Length 50mm SSC Dipoles", submitted to 1992 IISSC, New Orleans, March 1992

[2] M.J.Lamm, J.P.Ozelis, K.J.Coulter, S.Delchamps, T.S.Jaffery, W.Kinney, W.Koska, J.Strait and M.Wake "Bipolar and Unipolar Tests of 1.5m Model SSC Collider Dipole Magnets at Fermilab" Conf. Rec. 1991 IEEE Particle Accelerator Conference 2191 (1991)

[3] J.Strait, *et al.* "Quench Performance of Fermilab/General Dynamics Built Full Length SSC Collider Dipole Magnets", submitted to 1992 IISSC, New Orleans, March 1992

[4] well known method such as in: M.Kobayashi, K.Morimoto, H.Ishimoto and M.Wake, "Development of Superconducting Wires in KEK", proc. MT-5 793 (1975)

[5] P.Chaumette, *et al.* "A Large 1.8K Facility for Magnet Test", Adv. in Cryo. Eng. 35 269 (1990)

[6] M.N.Wilson, "An Improved Technique for Measuring Hysteresis Loss in Superconducting Magnets", Cryogenics 13 361 (1973)

[7] A.D.McInturff and D.Gross, "Magnetization Characterization Study for the Energy Saver/Doubler Dipoles", IEEE trans.Nucl.Sci. 28 3211(1981)

[8] M. Wake, D.A.Gross, R.Yamada D.Blatchley and M.E.Price "AC loss in Energy Doubler Magnets" IEEE trans. Mag. 15 137 (1979)