ELECTRICAL LOSS MEASUREMENTS IN A NbTi MAGNET*

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I. INTRODUCTION

Our work on ac losses has been mostly with NbTi wire magnets. These magnets were built for direct current use, but since they were available to us, it was convenient to use them while developing an electrical method of measuring losses.

First, I shall describe this electrical method and then describe some of our results. I shall talk mostly about results obtained since our earlier report.[1]

Most of the results that will be described here were made on a solenoid wound with Supercon NbTi wire which had a 0.015 in. diameter superconducting core in a copper wire of 0.03 in. over-all diameter. The wire was insulated turn-to-turn with a copper-oxide surface, and layer-to-layer with fiberglass cloth. The maximum field on axis was about 70 kG at 120 A. The winding had a 1.5 in. inner diameter, 4.5 in. outer diameter, and was 4.5 in. long.

II. LOSS MEASUREMENTS

This method of measuring losses depends on measuring the accumulated electrical energy entering the magnet over a period of several cycles. This is accomplished with the circuit shown in Fig. 1. The two key elements are a multiplying circuit to obtain instantaneous power flow between the magnet and power supply, and an integrator to keep track of electrical energy balance into the superconducting magnet.

The multiplier circuit works in the following way. It uses a semiconductor Hall device which develops an output voltage proportional to the product of input current to the Hall device, and magnetic field surrounding the device. A pair of potential leads inserted into the cryostat connects the test magnet to the Hall device through a resistor, so that current input to the Hall device is proportional to the magnet voltage. The Hall device is mounted in the gap of a small magnet which has been designed to give a magnetic field proportional to current in its windings. This magnet is put in series with the superconducting magnet so that the Hall device has a magnetic field input proportional to the current in the superconducting magnet. The inputs to the Hall device then, are proportional to voltage across the superconducting magnet and to current through it, and hence the output of the Hall device is a voltage proportional to instantaneous power into the superconducting magnet. This output voltage changes polarity with the direction of power flow.

The integrator uses a solid-state chopper-input operational amplifier with a feedback capacitor C, and a series resistor R, so that its output voltage is

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1. W.S. Gilbert, R.E. Hintz, and F. Voelker, Lawrence Radiation Laboratory Report UCRL-18176 (1968).

$$e_{out} = \frac{1}{RC} \int_0^T e_{in}(t)dt \quad .$$

Drift in the integrator circuit appears on the recorder as an equivalent power loss (except that it can have either sign), and so must be kept small. Typically, we had about 1 mV drift for a period of 1000 sec with a dynamic range of 10 V. For one particular multiplier constant this corresponds to a sensitivity of 1 J in a 1000 sec (or 1 mW) with a dynamic range of 10 000 J (stored in the magnet). We obtained a 1 J sensitivity on a cycle-to-cycle basis by using a digital voltmeter to read the voltage on successive minimum of the integrator output.

A section of the multiple recorder tracing illustrating how the loss information is presented, is shown in Fig. 2. Here the current had a triangular waveform with a peak amplitude of 10 A. The middle trace shows the accumulated energy over a number of cycles as the frequency was increased. The slope of the envelope is directly proportional to the ac losses. (The boil-off gas was almost constant over this run, and change in slope of the right-hand trace is due to changes in chart speed.)

Another kind of data sheet is shown in Fig. 3. In this case, the current waveform is trapezoidal with a constant dI/dt. Several cycles were run at each current. The constant current intervals were long enough to allow us to read the integrator output with a digital voltmeter. The trace labeled $\dot{B}$ shows an increasing amount of flux jumping as the current was increased, and more will be said about this later.

III. EXPERIMENTAL RESULTS

While making cycle-to-cycle loss measurements with a trapezoidal current waveform, we discovered that the first cycle at a new current level had considerably more energy loss than succeeding cycles. On a well stabilized coil we reached an asymptotic value within two or three cycles, while on another coil with less stabilization, it took four or five cycles. When there was a flux jump during a given cycle, the next cycle was extraordinarily lossy. Figure 4 shows several types of information relating to the cycle-to-cycle losses. The loss in joules/cycle is given as a function of the maximum current. Note that there is an envelope of asymptotic values obtained by pulsing a number of times at the same current. The first-cycle envelope was obtained by reversing the direction of current in the magnet at the beginning of each new current value to destroy the "ordering" effect. The energy loss on a cycle after a flux jump, or after increasing current without reversing direction always lay somewhere between the two envelopes. The maximum current of 116 A corresponds to about 67 kG on axis in the solenoid.

In general, the measured losses were within about a factor of two of values calculated by the loss equation in Hancox.[2] We were also able to measure losses over a partial cycle. For example, the current was varied from 0-10 A several times, then from 10-20 A several times, continuing on up to 100 A. The losses for this data are given in Fig. 4 as a partial-cycle envelope. Data for several values of ΔI are shown. Since we could record the maximum energy in the coil, as well as the minimum, we were able to measure the stored energy. Figure 5 shows the Q (stored energy/energy loss per cycle) as a function of maximum current during a cycle. The Q had a minimum at around 50 A, which probably corresponds to the current at which the average of the

2. R. Hancox, Proc. IEE (London) 113, 1221 (1966).

winding has complete field penetration in the superconductor. We can also calculate the inductance using the relationship: stored energy = $\frac{1}{2}LI^2$. The inductance is not constant, and is shown as a function of current in Fig. 5.

We are interested in ac losses at typical synchrotron repetition rates, and we have made several runs on our magnets at cycling rates as high as once a second, although these magnets were not designed to be pulsed, and even though the losses are very high. Figure 6 shows typical results on the magnet previously described. The loss in joules/cycle are shown as a function of frequency. The maximum current was 10 A, 14 A, and 20 A with triangular, sinusoidal, and trapezoidal waveforms. The 20 A data had to be taken a few cycles at a time in order to keep the magnet from going normal, and so only trapezoidal waveforms were used. At 14 A the magnet could only be pulsed for 8-10 cycles at the higher frequencies, and we suspect that the magnet was heating considerably. The different waveforms merely indicate that the losses are related to dI/dt, as well as maximum current.

All of these curves show a rise in losses at very low cycling rates. This is because of a constant 60 cycle ripple voltage. When the cycling times are very long, the loss due to ripple voltage accumulates over a longer period and makes data below about 0.05 Hz unreliable. Tests made last week with a transistor-regulated (very low ripple) power supply indicate that the losses are linear with frequency at the low end.

If we calculate eddy currents at 0.5 Hz with a 0-14 A triangular waveform in the copper, we obtain a loss of about 0.53 W. The magnet was wound on a thin stainless steel form and had end flanges of the same material. We calculate 0.272 W loss in each flange and 0.002 W loss for the tube. The total eddy current losses, then, should be

$$P_T = 0.53 + 2 \times 0.272 + 0.002 = 1.1 \text{ W} \quad .$$

From Figure 6, we see that the losses for 0-14 A at 0.5 Hz are about 9 J/cycle or 4.5 W. Thus, the measured eddy current losses are about four times larger than we can account for.*

Data are shown in Fig. 7 for trapezoidal current waveforms in which the losses were measured after each cycle. (Figure 3 is a typical data sheet for this kind of run.) The maximum current was increased while the dI/dt was held fixed. If one neglects the repetitive data for very low dI/dt because it contains appreciable losses due to ripple voltage, we see a definite increase in losses due to increasing dI/dt. There is a large scatter in data, however, because each pulse has a different loss, depending on the previous history of current, and whether a flux jump occurred in the previous cycle. At the higher currents this scatter is more pronounced as there were often several flux jumps in each cycle.

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* Note added in proof: It has been suggested by several people subsequent to this talk, that the copper oxide is not insulating well and that the extra losses are V^2/R losses due to parallel resistance paths from turn to turn. This kind of loss would have the right frequency dependence.

IV. CONCLUSIONS

We feel that this electrical method can be very useful for measuring ac losses in superconducting magnets, or in parts of such magnets. Since accumulated energy can be monitored at many currents during a cycle, it is possible to measure losses and stored energy during the parts of a cycle, which may help to separate some of the complicated phenomena taking place during the cycle.

We are building a magnet which will be a duplicate of the magnet that I have been describing, except that it will be wound with Airco multiple strand wire. The new wire has 130 strands of 1 mil NbTi wire in the same cross section of copper. We hope to compare its performance with its solid-wire sister in time to be presented later in this Summer Study.*

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*Note added in proof: The magnet tests on the Airco magnet were completed and are given by W.S. Gilbert, these Proceedings, p. 1007.

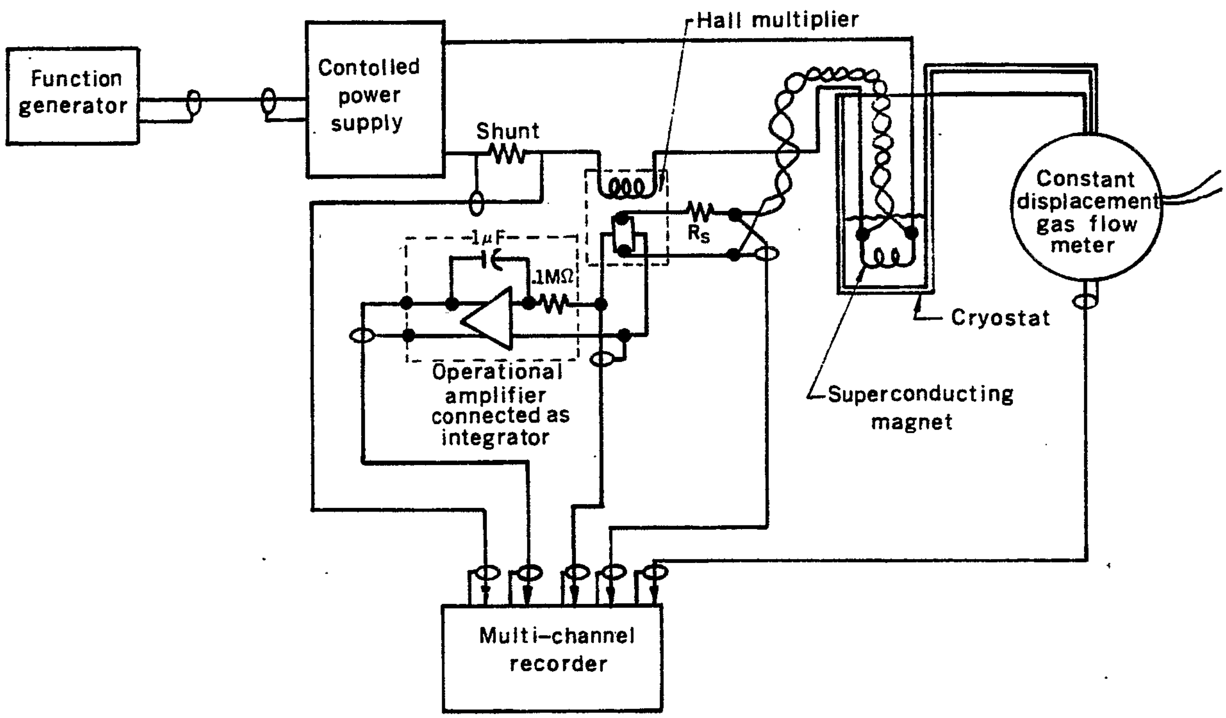

Fig. 1. Schematic representation of pulsed loss experiments.

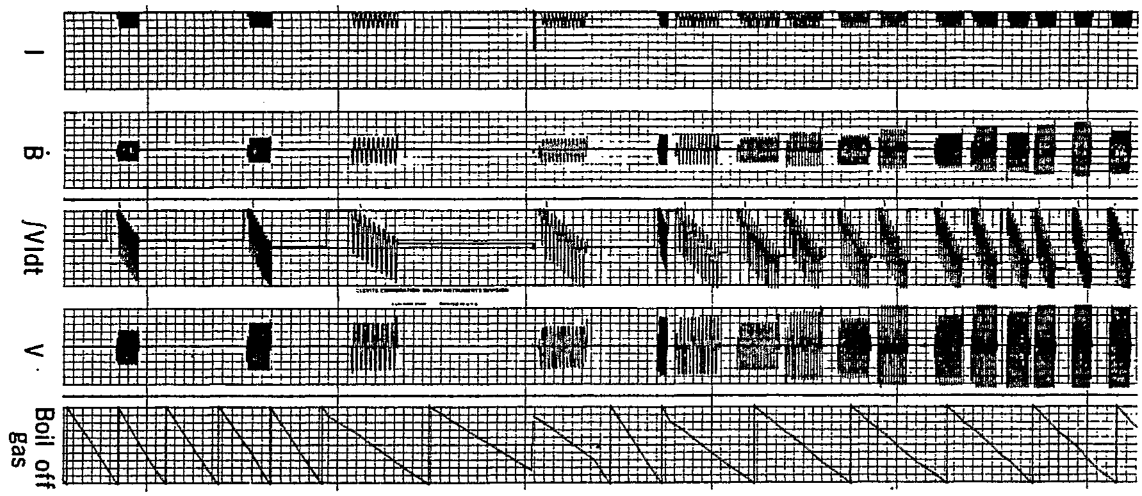

Fig. 2. Data for frequency run.

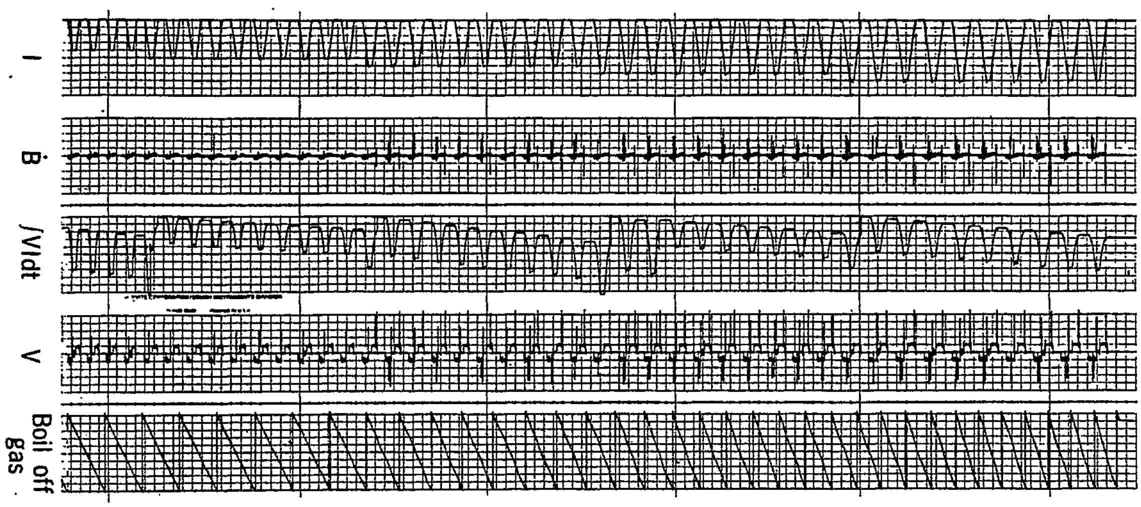

Fig. 3. Data for constant dI/dt run.

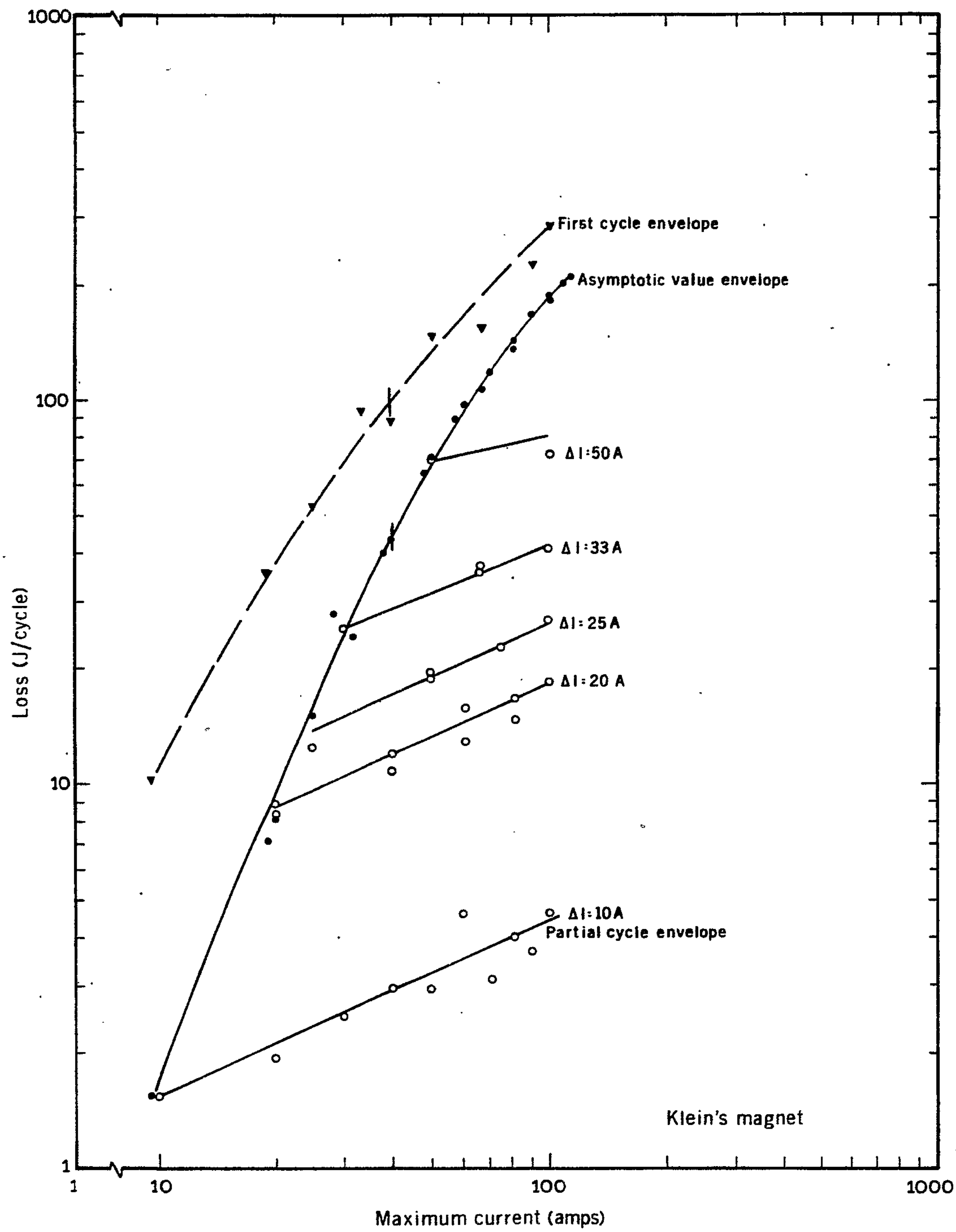

Fig. 4. Hysteresis losses.

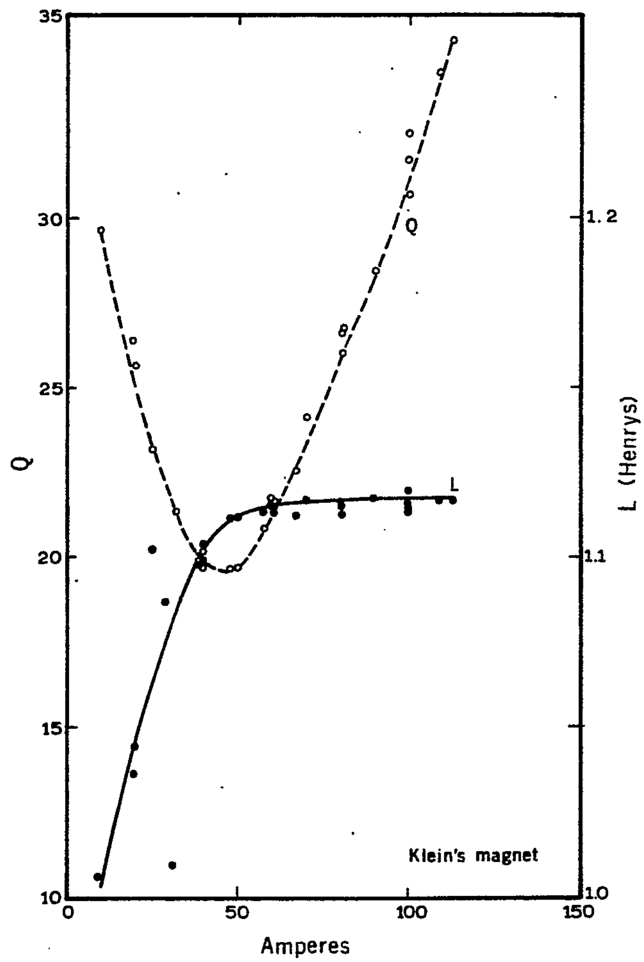

Fig. 5. Q and L as a function of maximum current.

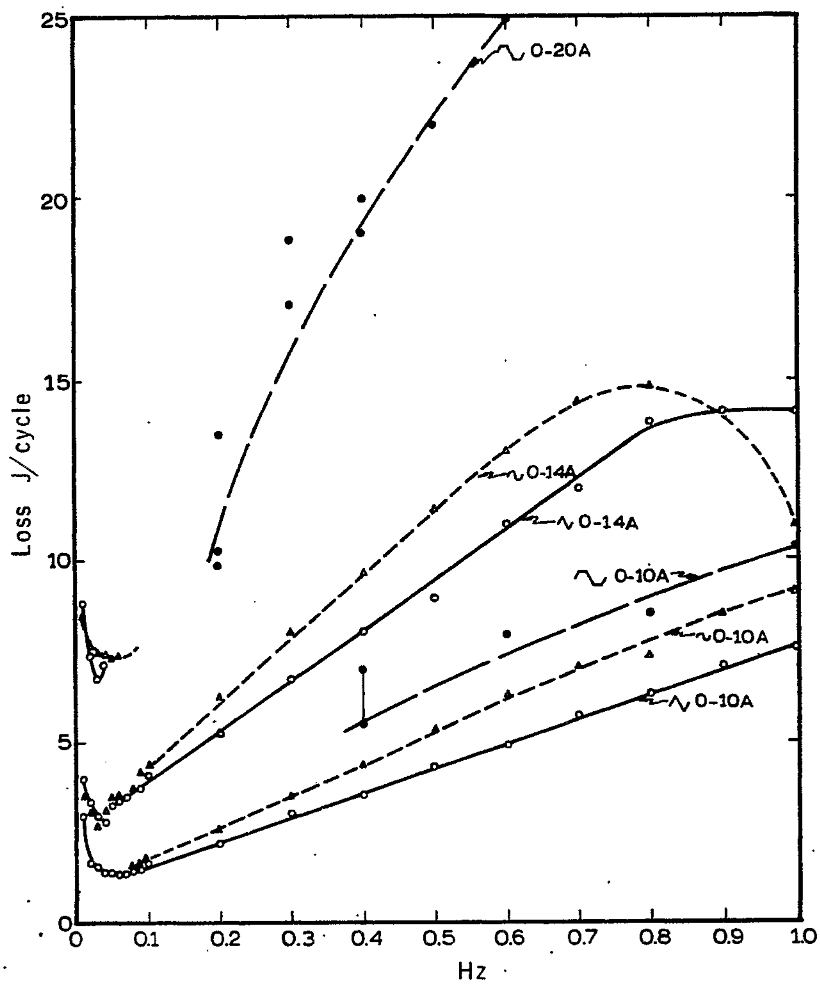

Fig. 6. Eddy current losses

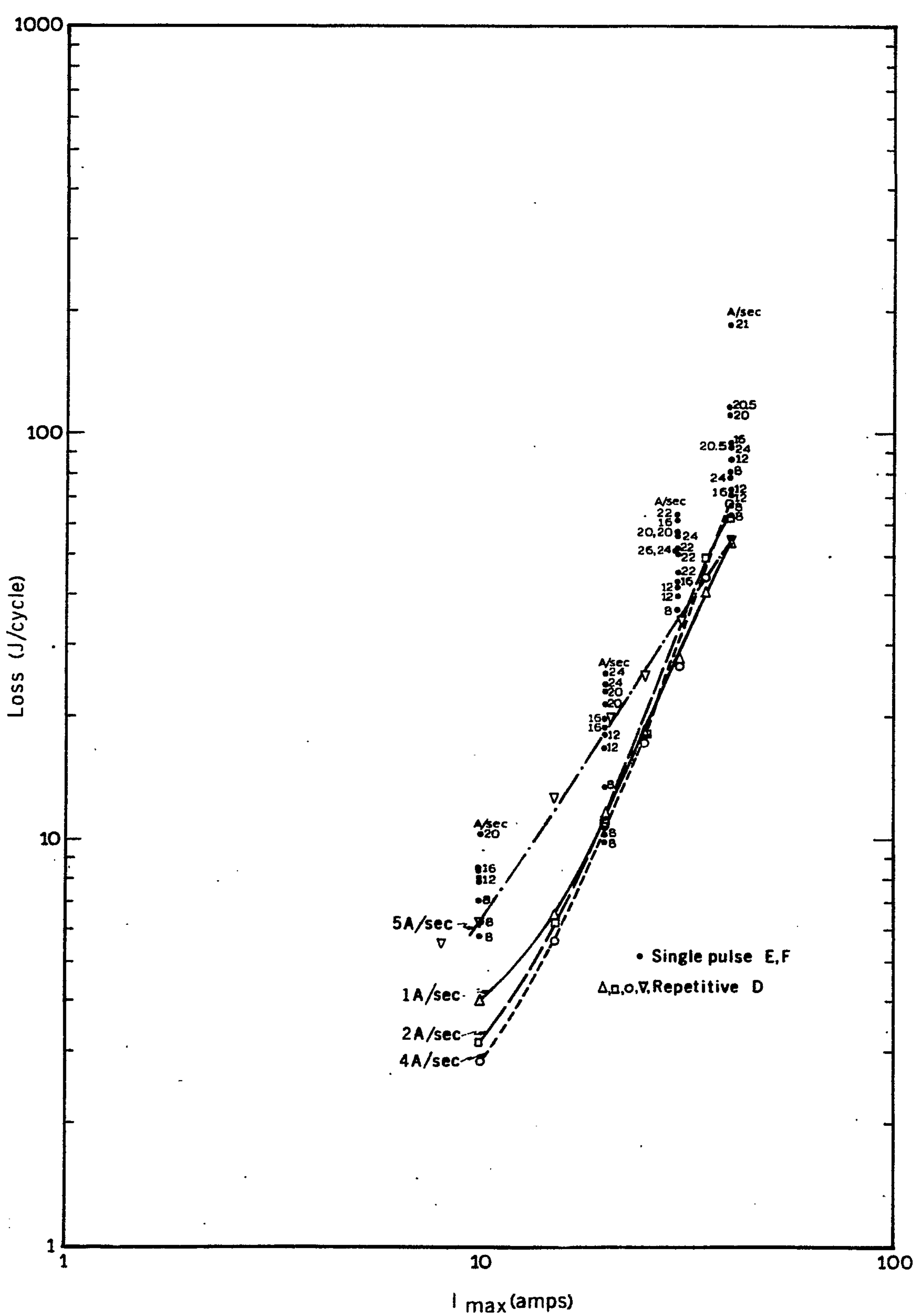

Fig. 7. Losses as a function of dI/dt.