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Informal Report

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DEPARTMENT OF APPLIED SCIENCE

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AC Losses for the Self Field of an AC Transport Current with a DC Transport Current Offset in High T_C Superconducting Magnet Coils for MagLev Application

by

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"Seek simplicity and distrust it."
- Alfred North Whitehead

Abstract

Self field loss measurements were made upon tape-wound 2223 superconducting helix coils. The self-field losses were produced by an AC transport current with a DC transport current offset. Losses were taken for single, double and triple tape windings, giving essentially monofilament, dual, and three filament cases.

Introduction

Although much research has been conducted concerning the losses of High T_c superconductors, very little has concentrated upon the self-field losses in an actual magnet arrangement. The coils studied here are designed for use as actual magnets in an industrial application. The losses measured here were varied over a range of AC current values for several different DC values, and over a range of frequencies. The currents were all AC sinusoids with a DC offset. All measurements were made at T = 77K.

Samples

The samples used were provided by Intermagnetics General Corp. (IGC). The samples were made by encasing the 2223 superconductor in a Silver sheath and then flattening to produce a tape. The tapes were then wound to produce a flat, helical disk. For the multiple tape variety, multiple tapes were placed together and then wound.

Sample Number	1	2	3
Material	2223	2223	2223
Manufacturer	IGC	IGC	IGC
No. of Cowound Tapes	1	2	3
Length of Tapes	---	9 meters	8.5 meters
No. of Turns	130	56	57
Winding Inner Diameter	---	1 inch	1 inch
Type	Wind and React	Wind and React	Wind and React

I_c @ 77K	---	17.5 A with 1μV/cm	21 A with 1 μV/cm
Overall Winding J_c	---	780 A/cm^2 @ 77K, Self field	650 A/cm^2 @ 77K, Self field

Experimental Arrangement

A computer controlled electrical testing arrangement was used. A voltage programmable DC Power Supply was used which could drive the necessary current and have little ripple. A function generator output was added to the output of a DC voltage source to give the necessary AC current with DC offset. This was then fed into the DC Power Supply. The DC power supply attempts to follow this voltage and, except at extremely high frequency, performed well. The isolation transformer is used to eliminate a ground loop produced by the earth ground of the function generator. A frequency counter is used to ensure even greater accuracy in frequency selection since the function generator is not perfect. The output of the DC Power supply is then sent through a shunt resistor and through the sample. The sample is submerged in liquid nitrogen inside of a dewar. The voltage readings from both the shunt and the sample are read into and stored in a digital oscilloscope. The scope is used in differential voltage input mode to avoid any ground loops. The voltage information stored in the scope is then sent to the computer for processing. The computer actually controls the entire procedure via a GPIB bus.

The computer then calculates the losses and peak-to-peak AC current values and records them. The calculation performed is the following:

$$P = \frac{f}{R_{shunt}} \times \int_0^T V_{shunt} \cdot V_{sample}\, dt$$

Where P is the power in Watts, f is the frequency in Hertz, R_{shunt} is the resistance of the shunt in Ohms, T is the period equivalent to 1/f, and V_{shunt} and V_{sample} are the voltages in Volts. This is simply an integration of V·I for the sample over one period because I_{sample} =

V_{shunt}/R_{shunt}. During the current rise, much of the energy supplied is stored in the sample. It is then returned to the power supply during the current decline. This comprises the pure inductive component of the sample. Since the inductive component of the sample (L·di/dt) is 90° out of phase with the sample current, it (Li·di/dt) cancels out to zero when integrated over one cycle. The remaining component which does not get returned to the power supply is dissipated in the sample. This comprises the AC loss.

This setup also allows for obtaining the pure loss waveform via digital bucking. The shunt voltage is used to buck out the sample voltage. First, one waveform is shifted 90° and then normalized to the other waveform. Then they are subtracted. The degree of bucking can be adjusted; thereby, reproducing a reasonable loss waveform.

An analog bucking arrangement was also used. A toroidal coil is inserted into the high current portion of the circuit by winding the high current wires around the toroid. This produces a signal (M·di/dt) which is then placed in series opposition with the sample voltage. Since it is very difficult to make L = M, a potentiometer is used to make L = pM, where p is the fractional amount of voltage division. The potentiometer can then be adjusted to reproduce the loss signal waveform on the oscilloscope. This analog bucking arrangement is similar to the one presented in Wilson[1]. There, however, an attempt is made to voltage divide the voltage from the sample, to obtain pL = M. This introduces a resistor in parallel into the high current portion of the circuit. This makes it necessary to subtract out the potentiometer loss from the loss calculation. Since the losses are small, a very accurate potentiometer would be needed which can handle high current. This is certainly difficult to obtain and therefore undesirable. Instead, by voltage dividing the toroid voltage, we exclude the need to include the potentiometer in the calculation, and put less constraint upon it's accuracy.

Both the bucked and unbucked arrangements should give similar loss values, since bucking only subtracts the inductive component, which cancels out to zero in the loss calculation. Both bucked and unbucked loss values were in good agreement. Also, both digital and analog bucking produced reasonable, and agreeable, loss signal waveforms.

Results

Single Tape

The single tape shows essentially a squared dependence for both the AC current dependence and the frequency dependence. This implies that a resistive eddy current component dominates the losses.

Double Tape

The double tape also shows a squared dependence for the AC current dependence, but shows a linear dependence on frequency. For low currents a slight increase from two is observed; whereas, for high currents a slight decrease from two is observed. This shows that although a resistive eddy current component dominates the losses, the hysteresis losses are also visible. For partial penetration, the hysteresis losses depend upon the cube of the AC current, and for full penetration the hysteresis losses go linearly with AC current. The frequency dependence, however, suggests a largely hysteretic component. This can be resolved by the fact that we are dealing with an untwisted multifilament conductor. As the twist length of a multifilamentary superconductor becomes large, shielding effects tend to reduce the dependence of eddy currents on frequency[2]. This explains the reduced frequency dependence.

The level of the DC transport current appears to have little, if any, effect upon the losses for the double tape. Data taken for 5ADC, 10ADC, and 15ADC all showed similar loss magnitudes. Also, the AC current and frequency dependencies were essentially the same.

Triple Tape

The triple tape has AC current attributes comparable to the double tape. Essentially, a squared dependence on AC current is seen, however, for low currents we see a deviation towards slightly greater than two. Of greater interest is the frequency dependence. The loss seems to depend upon the one-fourth power of frequency. Using similar arguments as given for the double tape, this shows that the outer two filaments can be playing a large role in shielding the inner filament. This would have a significant effect in reducing the frequency dependence.

The level of the DC transport current did have an effect on the losses for the triple tape. Although the dependencies upon AC current and frequency were similar for the 5ADC, 10ADC, and 15ADC cases, the magnitude of the losses decreased with higher DC transport current. The 15ADC losses were lower by as much as a factor of two than the 5ADC losses. This phenomenon might also be explained by the shielding current effects.

Acknowledgments

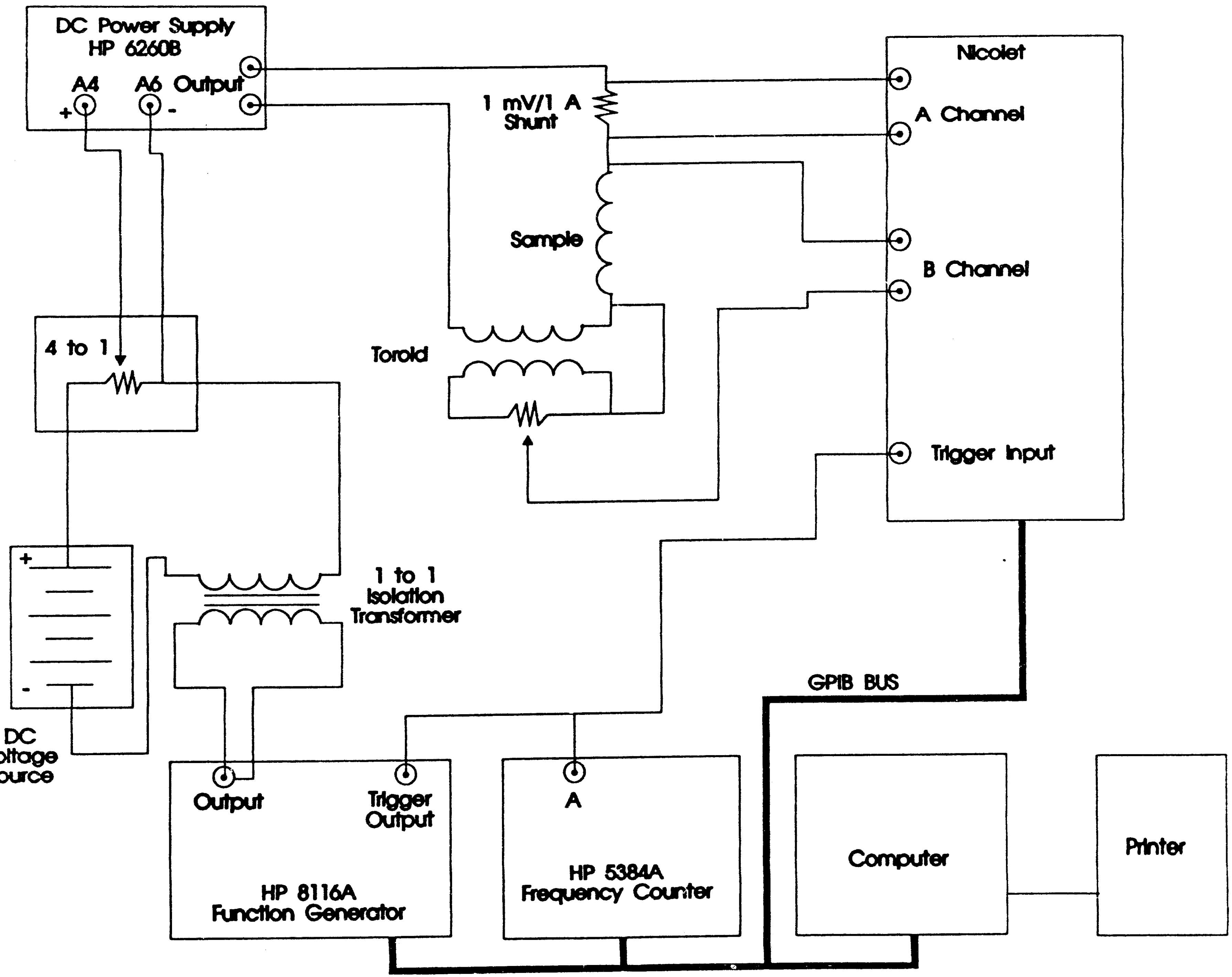
This work was supported, in part, by the DOE Brookhaven National Laboratory Summer Student Program. Sincerest thanks go to Dr. J. Orehotsky, both for experimental assistance and interesting theoretical investigations. Thanks also to Dr. M. Suenaga and Dr. J. Wegrzyn for encouraging and enlightening theoretical considerations and discussions.

References

1 Wilson, Martin N., Superconducting Magnets, Oxford University Press, 1983, pp. 253-254.

2 Carr, W. J., Jr., AC Loss and Macroscopic Theory of Superconductors, Gordon and Breach, 1983, pp. 111-113.

Table of Figures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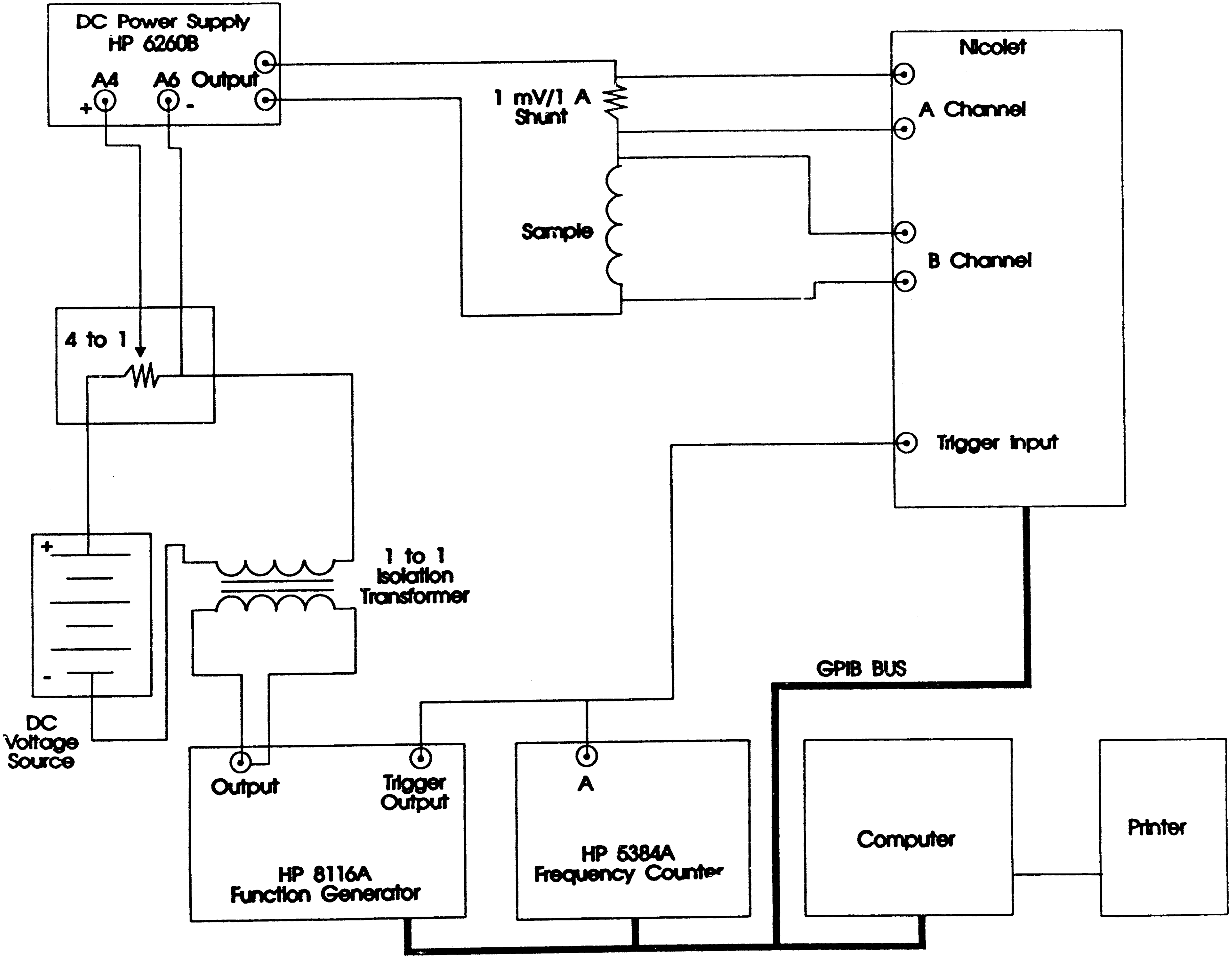
HP 6260B
A4
A6 Output
+
-
1 mV/1 A
Shunt
Nicolet
A Channel
Sample
B Channel
4 to 1
Toroid
Trigger Input
+
-
1 to 1
Isolation
Transformer
GPIB BUS
DC
Voltage
Source
Output
Trigger
Output
A
HP 8116A
Function Generator
HP 5384A
Frequency Counter
Computer
Printer

Fig. 2



DC Power Supply
HP 6260B
A4
A6
Output
+
-
1 mV/1 A
Shunt
Sample
Nicolet
A Channel
B Channel
Trigger Input
4 to 1
1 to 1
Isolation
Transformer
+
-
DC
Voltage
Source
Output
Trigger
Output
HP 8116A
Function Generator
A
HP 5384A
Frequency Counter
GPIB BUS
Computer
Printer

Fig. 1

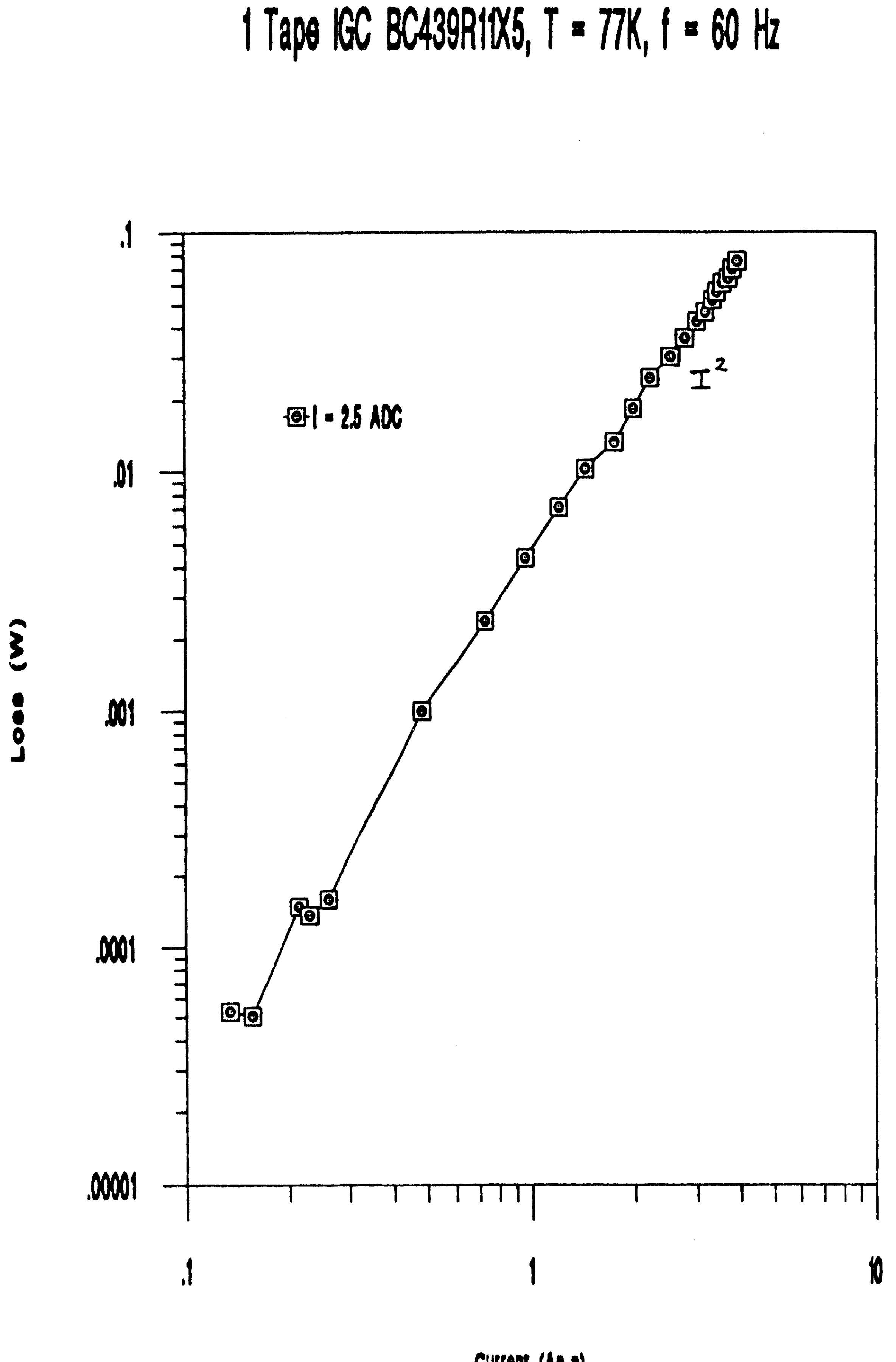

1 Tape IGC BC439R11X5, T = 77K, f = 60 Hz
Loss (W)
.1
.01
.001
.0001
.00001
I = 2.5 ADC
I²
.1
1
10
Current (Ap-p)

Fig. 3

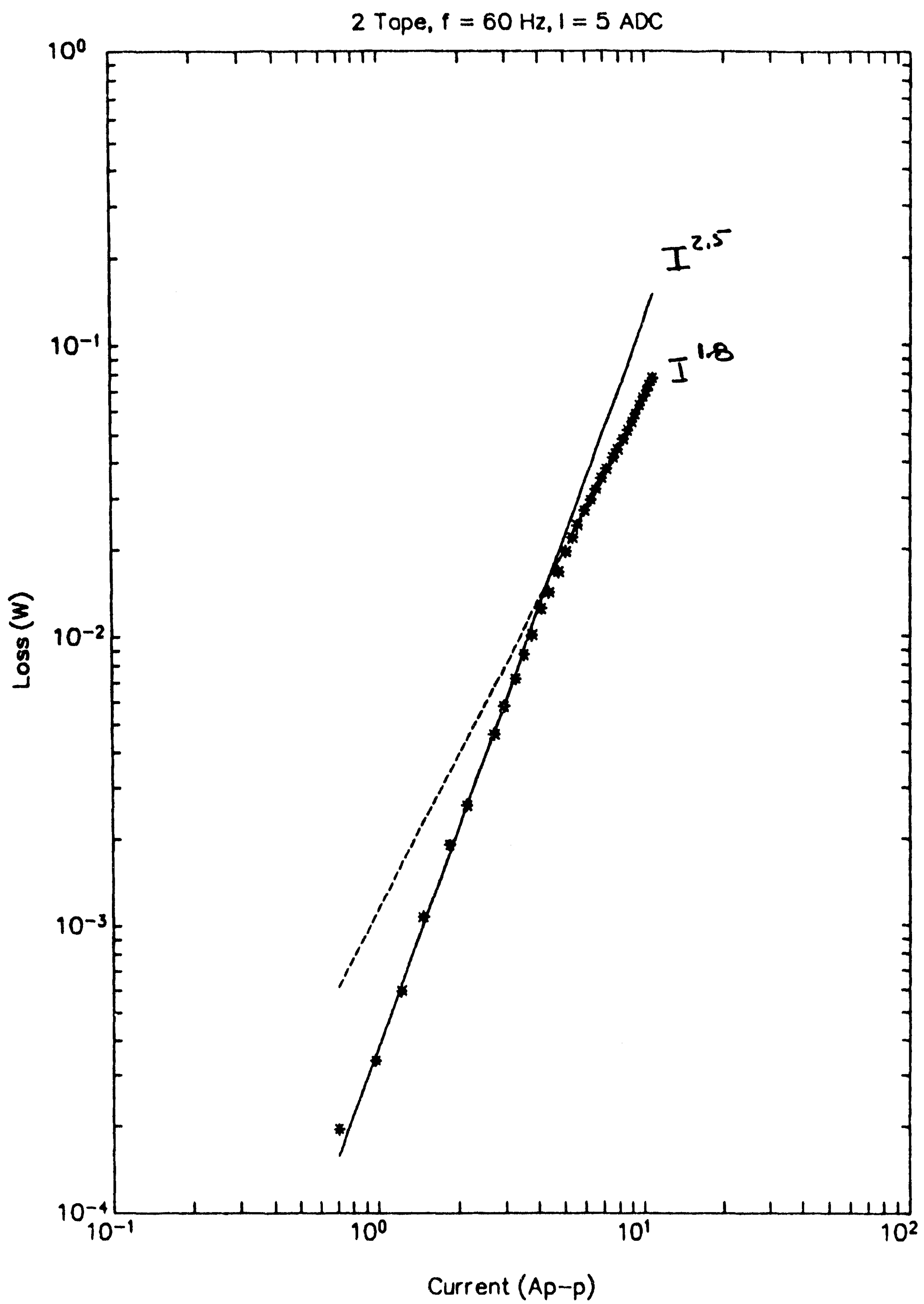

2 Tape, f = 60 Hz, I = 5 ADC
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Loss (W)
10^{-1}
10^0
10^1
10^2
Current (Ap-p)
$I^{2.5}$
$I^{1.8}$

Fig. 4

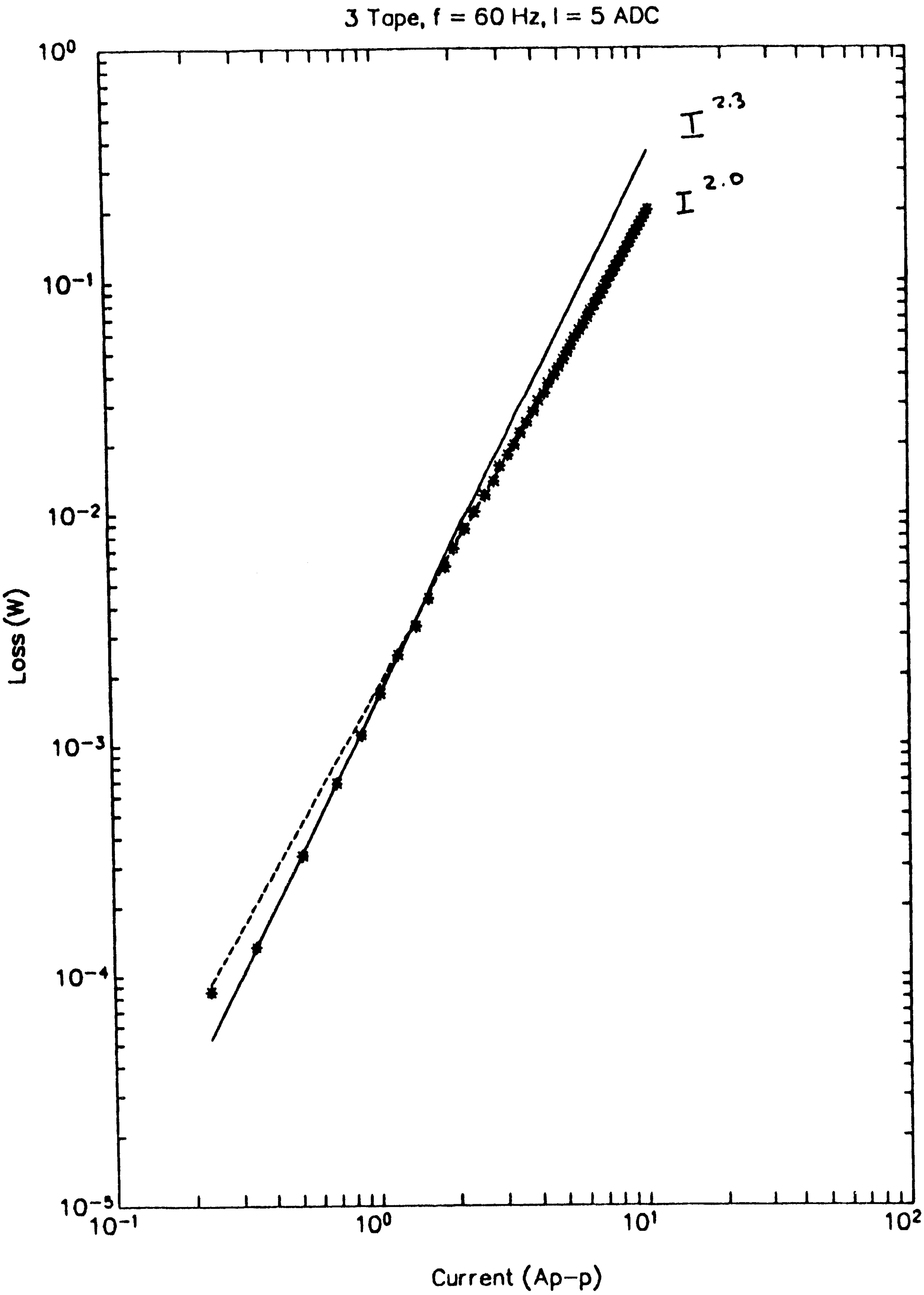

3 Tape, f = 60 Hz, I = 5 ADC
Loss (W)
Current (Ap-p)
I 2.3
I 2.0
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-1
10^0
10^1
10^2

Fig. 5

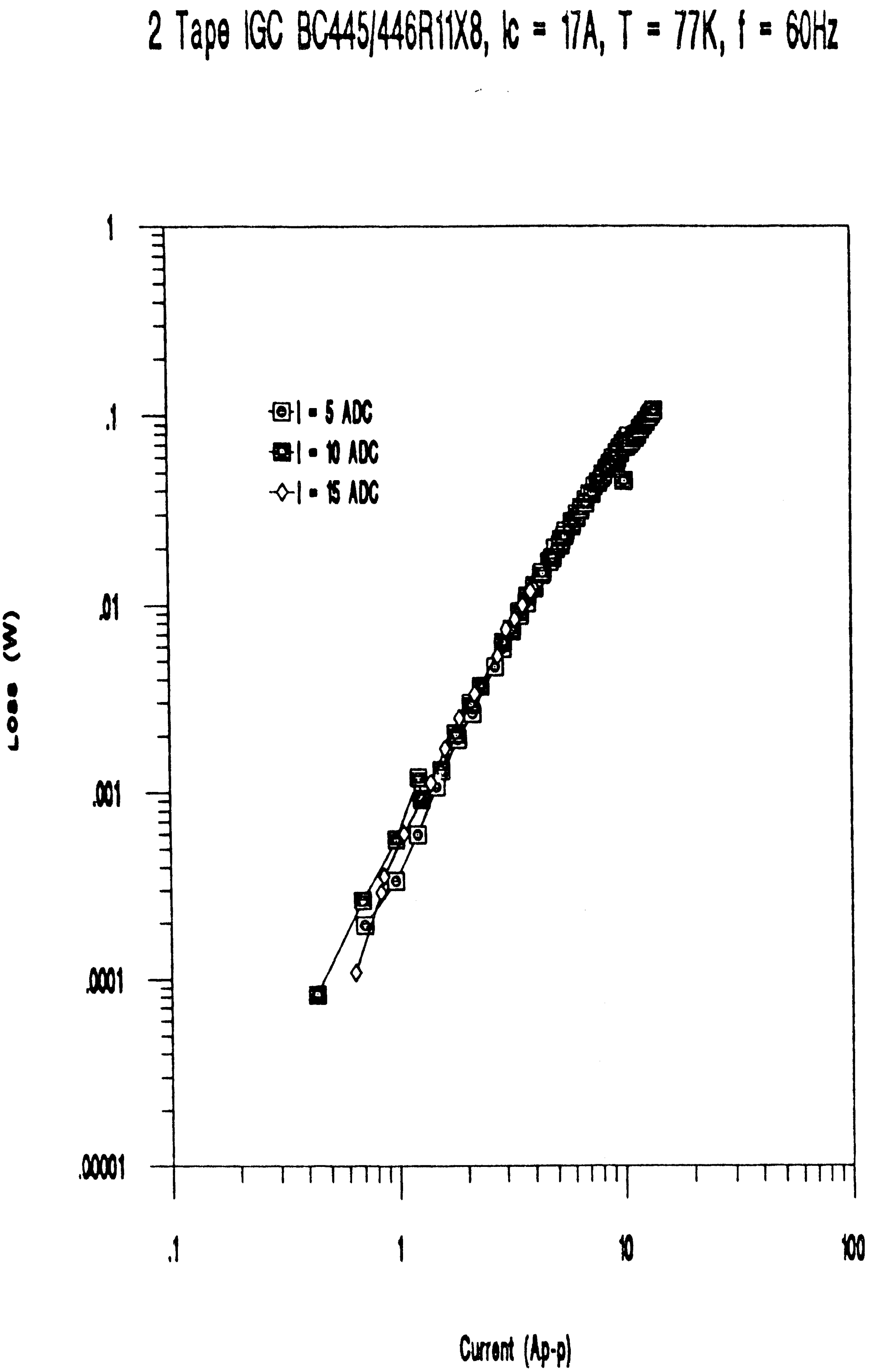

2 Tape IGC BC445/446R11X8, Ic = 17A, T = 77K, f = 60Hz
I = 5 ADC
I = 10 ADC
I = 15 ADC
Loss (W)
1
.1
.01
.001
.0001
.00001
.1
1
10
100
Current (Ap-p)

Fig. 6

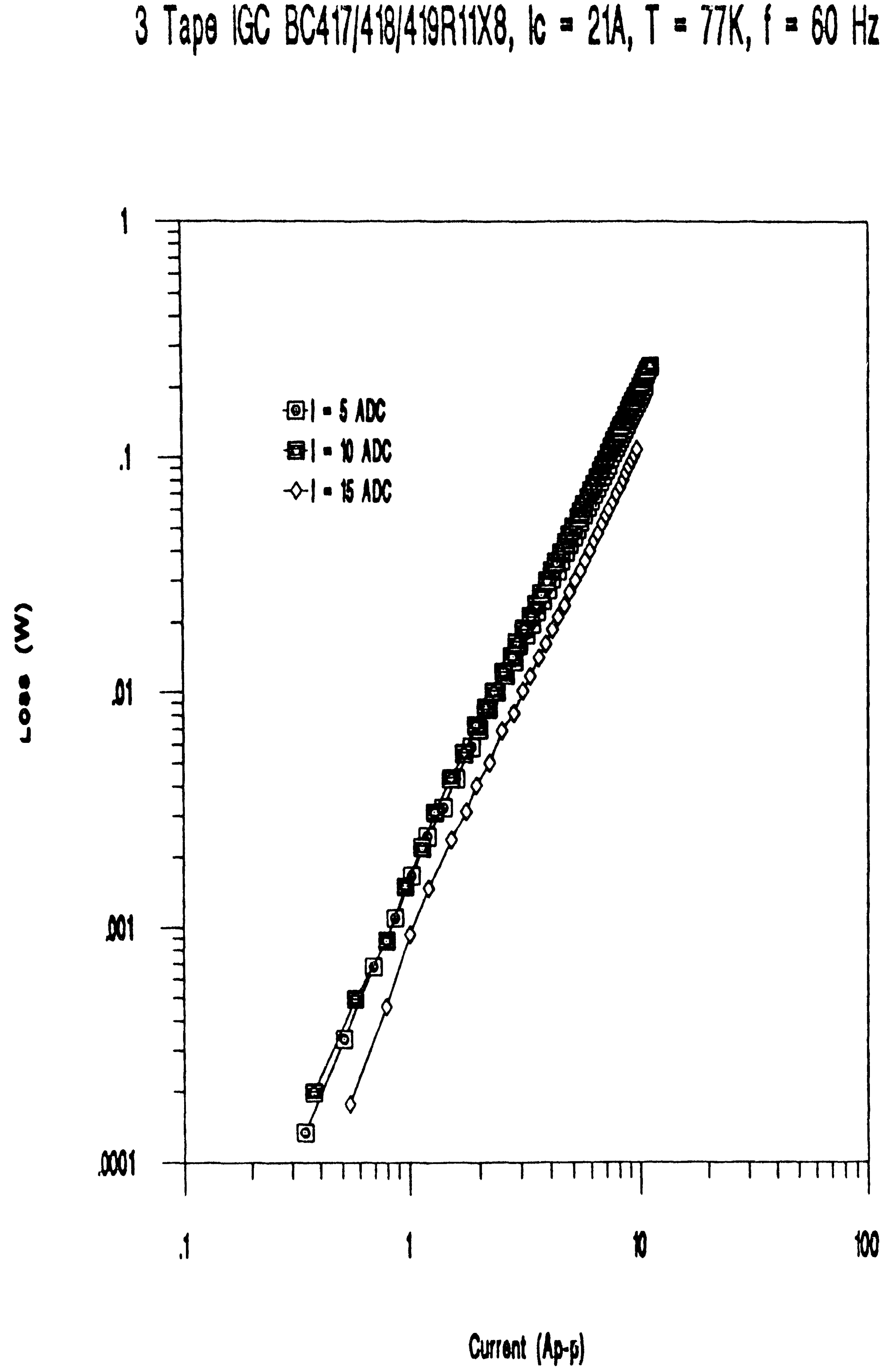
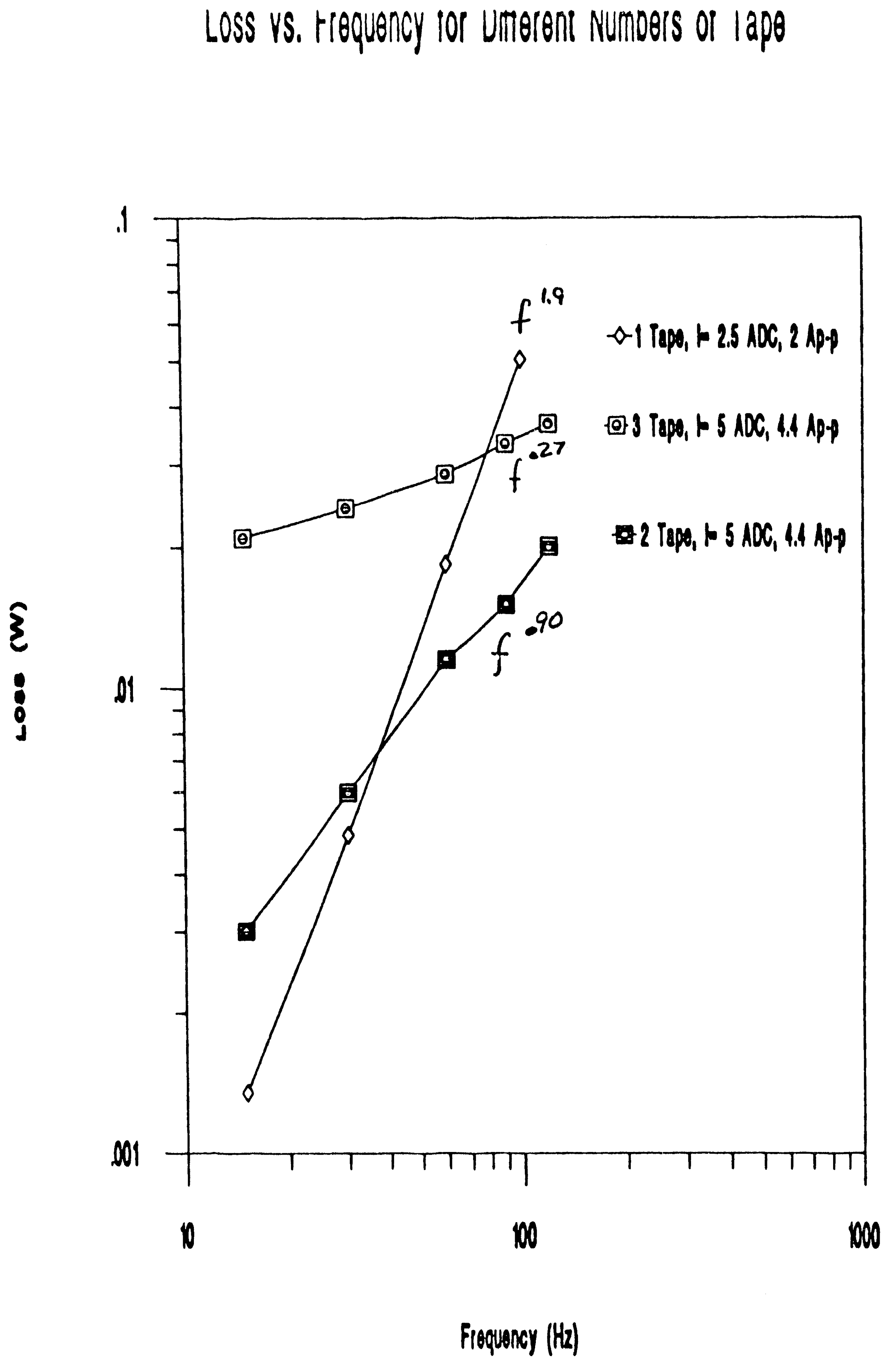

3 Tape IGC BC417/418/419R11X8, Ic = 21A, T = 77K, f = 60 Hz
I = 5 ADC
I = 10 ADC
I = 15 ADC
1
.1
.01
.001
.0001
Loss (W)
.1
1
10
100
Current (Ap-p)

Fig. 7



Loss vs. Frequency for Different Numbers of Tape
Loss (W)
.1
.01
.001
10
100
1000
Frequency (Hz)
f 1.9
f .27
f .90
1 Tape, I= 2.5 ADC, 2 Ap-p
3 Tape, I= 5 ADC, 4.4 Ap-p
2 Tape, I= 5 ADC, 4.4 Ap-p

Fig. 8

Loss vs. AC Current for Different Numbers of Tape

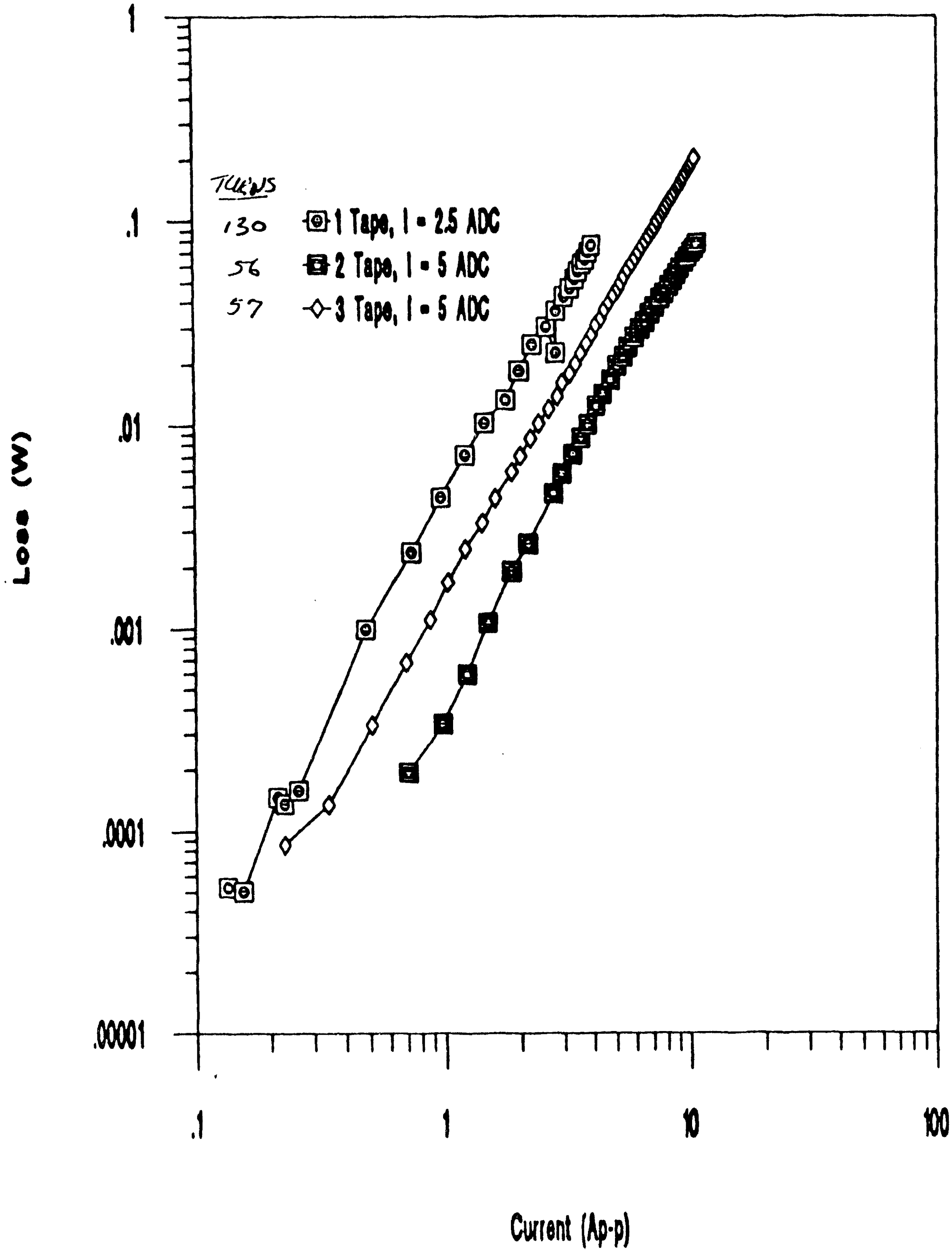


Fig. 9

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