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LOSSES IN PULSED SUPERCONDUCTING MAGNETS*

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Summary

AC, or cyclic, energy losses were determined in a series of geometrically similar solenoids wound with single-core, untwisted-multicore, and twisted-multicore composite superconductor. The twisted-multicore has markedly reduced losses compared with the other alternatives.

A larger solenoid was wound with twisted-multicore rectangular conductor. This same type conductor was also used in a dipole (bending) magnet geometry both with and without a cylindrical iron return yoke.

Magnetization measurements on multicore composite as a function of mechanical twist rate and magnetic sweep are presented.

Theoretical loss as a function of NbTi filament size and maximum swept field are presented. The agreement of the above measurements with theory is discussed.

Introduction

The feasibility of pulsed superconducting magnets in accelerators depends critically upon the heat generated, which must be removed by 4.2°K liquid helium. The attendant temperature rise tends to drive the superconductor resistive, or "normal". The energy loss for a cyclic sweep of magnetic field is akin to hysteresis, and

*Work done under the auspices of the U. S. Atomic Energy Commission.

for single-wire filaments, loss per unit volume is proportional to wire diameter. Practical accelerator magnets appear to require 0.001-in.-diam (25μ) or smaller wire. Coextrusion of many filaments of ductile NbTi imbedded in copper or copper alloy enables one to produce the required fine filaments within a strong, high-current conductor. However, the normal material causes increased losses through electrical coupling of the filaments. This coupling can be reduced with high-resistivity normal material and by twisting the entire matrix.

These cyclic losses have been measured in single-core NbTi superconductor-wound solenoids and the results and comparison with theory reported by us.[1] The coextruded multicore conductor resulting in filament sizes between 0.001 and 0.002 in. did not become generally available until late 1968. P. F. Smith and his co-workers pointed out that the potential advantage of small filament size would not be realized if the normal matrix material were able to electromagnetically couple the filaments.[2] Dependence of matrix coherence length ℓ_c on the properties of the composite conductor and the rate of magnetic field change $\dot{H}$ is

$$\ell_c^2 \approx 10^8 \lambda J_c d\rho/\dot{H}, \tag{1}$$

where λ is the space factor, J_c is the current density (A/cm^2), d is the diameter of the superconducting filament (cm), and ρ is the electrical resistivity of normal material (ohm-cm). If the wire is twisted so that half the twist distance is smaller than ℓ_c, the filaments are not coupled, and the cycle loss per superconductor unit volume should correspond to the filament diameter, d. If the half-twist distance is greater than ℓ_c, the filaments are coupled, and the cycle loss increases to that corresponding to the much larger dimension of the entire matrix.

Experimental Magnet No. 1 - Small Solenoid

A solenoid wound with Supercon * .015/.030 in. conductor was tested for cyclic, or pulsed, energy loss.[1,3] Developmental material was supplied by Airco.** This multicore material has the same quantity of superconductor and the same OD, but the core is subdivided into 131 0.0013-in.-(33μ) diam. filaments. This material was wound into a solenoid of the same dimensions as that of the single-core conductor the magnet was tested for cyclic energy loss.[4] This Airco material was subsequently twisted 1.5 turns per inch (0.6 turns per cm) and rewound into the same solenoid configuration. The pulsed loss data for this last magnet are included in this report, together with relevant data from the previous two tests. The conductor was next insulated with Formvar and the magnet rewound for the fourth time. These data appear below.

Figure 1 is a photograph of a test magnet. An important feature of the construction of the first three magnets is that the conductor surface is chemically oxided, and this oxide serves as the turn-to-turn insulation. Fiberglass cloth is used for interlayer insulation. This method of coil insulation is not completely satisfactory. Details of the experimental apparatus and procedure are presented elsewhere.[1,3]

Results - Magnet No. 1

The solenoids' specifications are: Winding: ID = 1.5 in., OD = 4.5 in., length = 4.5 in.; Inductance ≃ 1.2 henry; Maximum field on axis = 70 kG at I = 120 A; Stainless steel flanges and winding spool.

All three test magnets performed at their respective short sample limits; the multicore Airco conductor has slightly lower J_c than the single-core Supercon conductor. The heat transfer

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*Supercon Division, Norton Company, Natick, Massachusetts

**Air Reduction Co., Inc., Murray Hill, New Jersey characteristics are such that the magnet goes normal at about 8 W average power, although slightly higher power can be dissipated during single-pulse operation. After the Formvar insulation was applied, only about half the above power could be dissipated.

Figure 2 displays the cycle loss vs I_{max} for the Formvar-insulated twisted multicore magnet (No. 4 in this series) for I_{max} = 40 A and 20 A. The data are somewhat smoother than the corresponding oxide insulated case, but the losses are similar and the frequency dependence still pronounced and not due to high resistance electrical shorts. Eddy current losses calculate to be much too low to yield the measured frequency dependence and the comparison of the slopes for identical $\dot{B}$ for the two currents, shown on Fig. 2, likewise militate against an eddy current explanation. We propose that as the frequency is increased, one has a gradually increasing coupling of the multicore filaments of superconductor. In a magnet, of course, there is a distribution of field strengths at a given current and different $\dot{B}$'s throughout the magnet, so that the coupling condition is difficult to unfold from the entire magnet behavior curve.

For the new data in Fig. 2 we made energy loss determinations though a double Dewar boiloff helium gas collection method simultaneously with our usual electrical Hall-multiplier method. The two methods gave data agreeing to better than 20%. At the low frequency end of the loss curves there is little difference in the loss data from the Formvar and oxide insulated magnets.

Figure 3 presents the magnet loss data vs I_{max} for the single core, untwisted-multicore, and twisted-multicore, conductors at low frequency. Clearly the losses are reduced when smaller superconducting filaments are used and one must twist the conductor if one is to realize these benefits (in a copper matrix, at least).

Experimental Magnet No. 2 — Large Pulsable Solenoid

A larger pulsable solenoid was fabricated from a developmental superconductor supplied by Airco. Three hundred sixty cores of NbTi are twisted 1.25 turns per inch in a rectangular copper matrix .050" x .125" (1.27 mm x 3.18 mm), the individual filaments have a diameter of 2.7 mils (69μ). Insulation is provided by a spiral wrap of 5-mil-thick epoxy resin glass cloth. The winding spool is a polyester fiberglass tube and the end flanges are made from epoxy fiberglass. Holes are drilled in the spool and end flanges to facilitate helium permeation. Some of these features can be seen in Fig. 4. The solenoid specifications are:

Winding:

ID	=	5.3" = 13.5 cm
OD	=	6.7" = 17.0 cm
Length	=	8.4" = 21.4 cm
Inductance	=	23 milli-henry
Maximum Transition Current	=	1510 A (material short sample at B_{max})
B_o	=	43.8 kG
B_{max}	≈	47 kG
$(\dot{B}_o)_{max}$	=	4.6 kG sec^{-1}; limited by power supply

The loss per cycle vs frequency data for this magnet are shown in Fig. 5. Again a strong frequency dependence is apparent, for a magnet wound on a non-metallic form. In Fig. 6, are the low frequency cycle loss vs I_{max} data.

Experimental Magnet No. 3 — Dipole Magnet

Figure 7 shows a test dipole with its cylindrical shell iron return yokes. The magnet has been run with and without the iron shells. The conductor used is the 360 core twisted, rectangular, Airco material used in the solenoid discussed above. This magnet is a prototype beam transport element, and no attempt was made to make it low loss under pulsed application; an aluminum bore tube and aluminum winding islands were used which could give appreciable eddy current losses. However, we routinely pulse our magnets to obtain a variety of loss information and some data are available. The dipole specifications are:

Winding:

ID	= 4.1" = 10.4 cm
OD	= 5.4" = 13.7 cm; 4 layers of conductor
Length	= 16.2" = 41.2 cm
Inductance	≃ 19 milli-henry; 4 layers

A. Two layers of conductor — no iron. The first 2 current layers contain 0.6 the turns of the entire 4 layer magnet and, roughly, produce 0.6 the central field for a given current. The magnet was tested with 2 layers, and no iron, and a transition current of 1900 A was achieved. This current corresponds to a central field of 15 kG and a maximum field at the end loop conductors somehwat over 20 kG. The pulse data taken are shown on Fig. 8. There is a strong frequency dependence. We have not yet separated the eddy current effect from the superconductor twist-$\dot{B}$ effect.

B. Four layers — no iron. The entire 4 layer magnet performed very well as it reached short-sample performance — it is not charge rate sensitive, it is stable, and it has relatively low cyclic loss. A high resistance electrical short in one of the outer layers prevented meaningful loss measurements to be taken. A transition current of 1680 A was obtained. This corresponds to a central field of 28.4 kG and a maximum field at the end loop conductors of 35 kG, for which the 1680 A is essentially short-sample current.

C. Four layers - with iron. The entire magnet was next run in the 2 concentric cylindrical iron shells visible in Fig. 7. These shells are in the liquid helium, are together 1.4 inches in radial thickness, and are largely saturated at high excitation. The transition current of 1510 A corresponds to a central field of 35.0 kG and a maximum field at the end loops of over 40 kG, for which the above current is short-sample behavior. At this 1510 A excitation, the iron return yoke adds 9.2 kG central field, compared to the 4 layer-no iron case at 1510 A.

Cyclic loss data are presented in Fig. 9.

Magnetization Experiments

The magnetization of a superconductor can be measured with a pair of pickup coils in a uniform magnetic field, with the superconductor near one of the coils. If one pulses the magnetic field from zero to some H_{max} and back to zero, the area under the magnetization curve is proportional to the cyclic energy loss experienced by the superconductor.

$$\text{Loss/cycle} = \oint M dH \qquad (2)$$

Cryomagnetics* composite superconductor with 85 NbTi cores in a 20 mil copper matrix was used for magnetization tests; each core has a diameter of 1.2 mils or 30μ. One series of test used the conductor as drawn although some twist may have occured during winding. A second series has the conductor twisted about its axis 3 T in^{-1}. The relative areas, or losses, as a function of $\dot{B}$ are shown on Fig. 10. One can see the dramatic decrease in loss with twisting, and the increase in loss with $\dot{B}$. Qualitatively this behavior is similar to that of the experimental magnets which have a similar loss curve for each incremental length of wire.

There has been speculation that a multi-core wire will behave like a solid wire of the same outside diameter if the $\dot{B}$ is large enough to make the twist ineffective. In this case the ratio of loss at high

* Cryomagnetics Corp., Denver, Colorado

frequency to the loss at low frequency should be equal to the ratio of the wire size to the filament size.

Perhaps the most important aspect of these curves is that the ratio of high frequency loss to the low frequency loss is much smaller than the wire diameter to filament diameter ratio.

Comparison of Loss Results

At the low frequency end of the cyclic loss curves we can arrive at the following comparisons for the 3 magnet systems tested; all at a central field maximum of 28 kG:

a) Magnet No. 1, 1.3 mil (33μ) diameter cores, 131 filaments

U_L = Loss per cycle = 13 Joules

Volume of NbTi = 10.7 in^3

$U_L/Vol = 1.22\ J/in^3$

b) Magnet No. 2, 2.7 mil (69μ) diameter cores, 360 filaments

$U_L = 104$ J

$Vol = 22.3\ in^3$

$U_L/Vol = 4.67\ J/in^3$

c) Magnet No. 3, dipole with iron, 2.7 mil diameter cores

$U_L \approx 120$ J

$Vol = 20.4\ in^3$

$U_L/Vol = 5.9\ J/in^3$

One would expect the unit loss (U_L/Vol) for c) to be higher than b) because the end loops of a dipole have higher fields than any conductors in a solenoid, for the same central fields in the two cases. Both b) and c) differ from a) in that their NbTi filaments are twice the diameter. In addition a) has a thicker winding than b) and c) and so the field distribution is quite different.

Loss Theory

Using a Kim-type relationship for the J_c for the NbTi superconductor we used in our various tests, we are able to match our material M-H short-sample curves to within 10% from 10 to 60 kG.

With this J_c function one can calculate expected cyclic loss for sheets of material of superconductor as a function of the maximum field at the surface of the conductor. Such a relationship is shown on Fig. 11. It is of interest to notice that, at high fields, the losses do not increase as the first power of the field but rather as the square root. Similar results were obtained by Hancox[5] for NbZr, as appears in Fig. 11, for a thickness which is not obvious to us.

In going from this sheet loss to magnet loss one must treat the filaments in a somewhat arbitrary way. We get fair agreement between theory and experiment, using solenoid No. 1's actual distribution of magnetic field, if we use the projected area of the round filaments on the thin sheets of Fig. 11. If we use the surface area of the filaments as corresponding to one surface of the thin sheet, then a factor of $\pi/2$ enters. See Fig. 12.

More integrations over the actual field distributions for the various magnets tested will be carried out and we will be able to check the measured loss vs those calculated more closely.

Acknowledgments

The extensive design, fabrication, operation, instrumentation, and computation effort involved in this long series of experiments is clearly beyond the efforts of just the authors of this paper. The entire Superconductivity Group of the LRL Accelerator Design Group was involved. They are: R. Acker, A. Borden, W. Chamberlain, S. Clark, W. Eaton, M. Green, R. Kilpatrick, F. Toby, and W. Vogen. The magnetization apparatus was built and first operated by M. Suenaga, now at Brookhaven National Laboratory. We are pleased to acknowledge the continued interest in and support of these studies by Dr. E. J. Lofgren.

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3. F. Voelker, Lawrence Radiation Laboratory report, UCRL-18374, July 1968 and 1968 Brookhaven Summer Study, UAC-15655.

4. W. S. Gilbert, 1968 Brookhaven Summer Study, UAC-15655.

5. R. Hancox, in <u>Proceedings of the IEEE</u>, Vol. 113, No. 7, July 1966.

CBB 682-749

Fig. 1

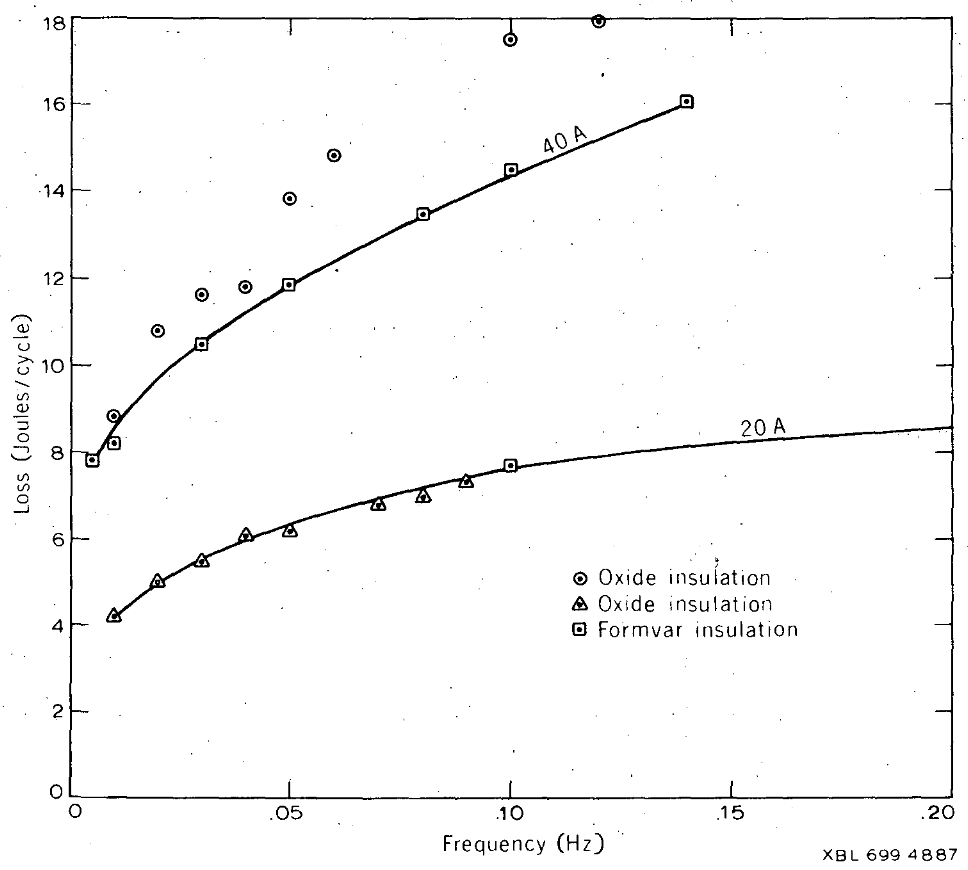

18
16
14
12
10
8
6
4
2
0
Loss (Joules/cycle)
0
.05
.10
.15
.20
Frequency (Hz)
40 A
20 A
Oxide insulation
Oxide insulation
Formvar insulation
XBL 699 4887

Fig. 2

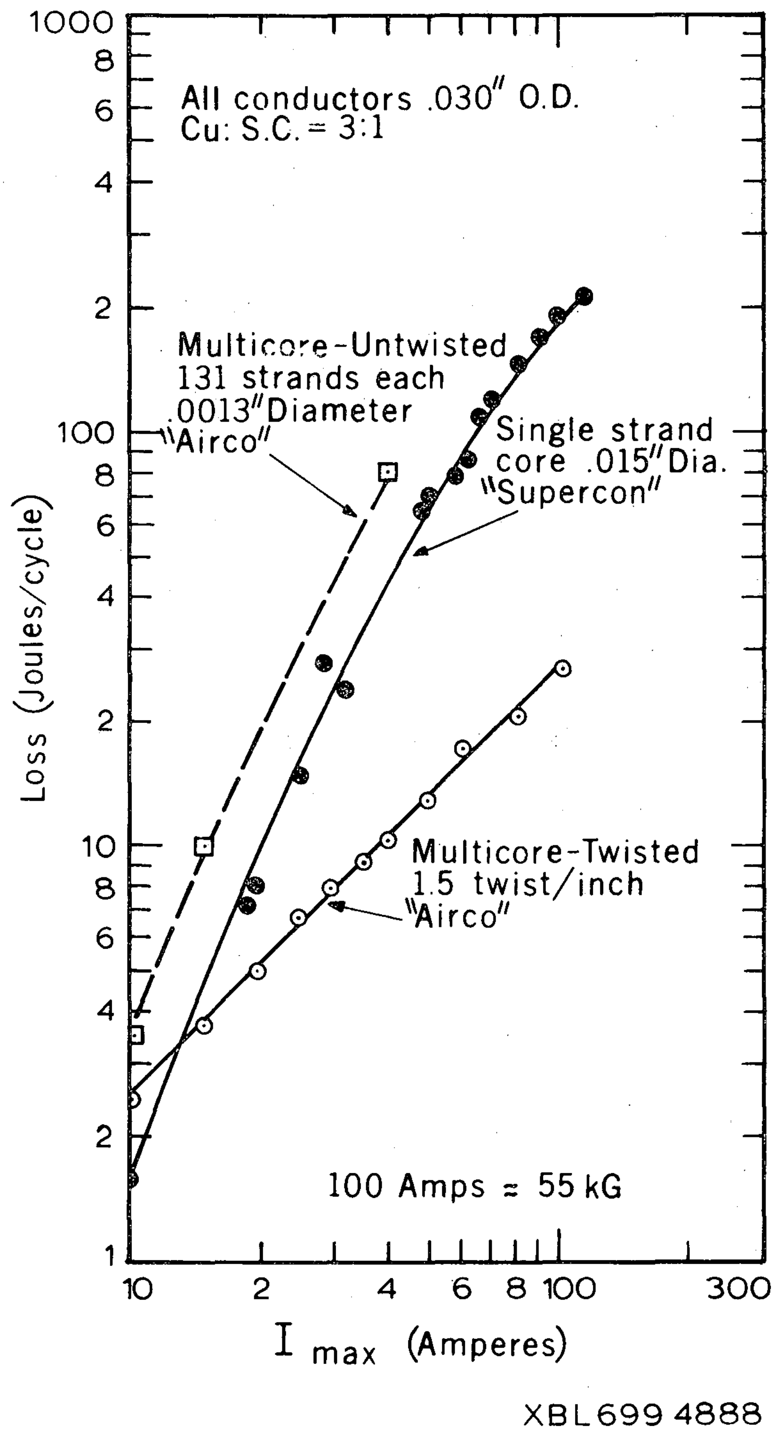
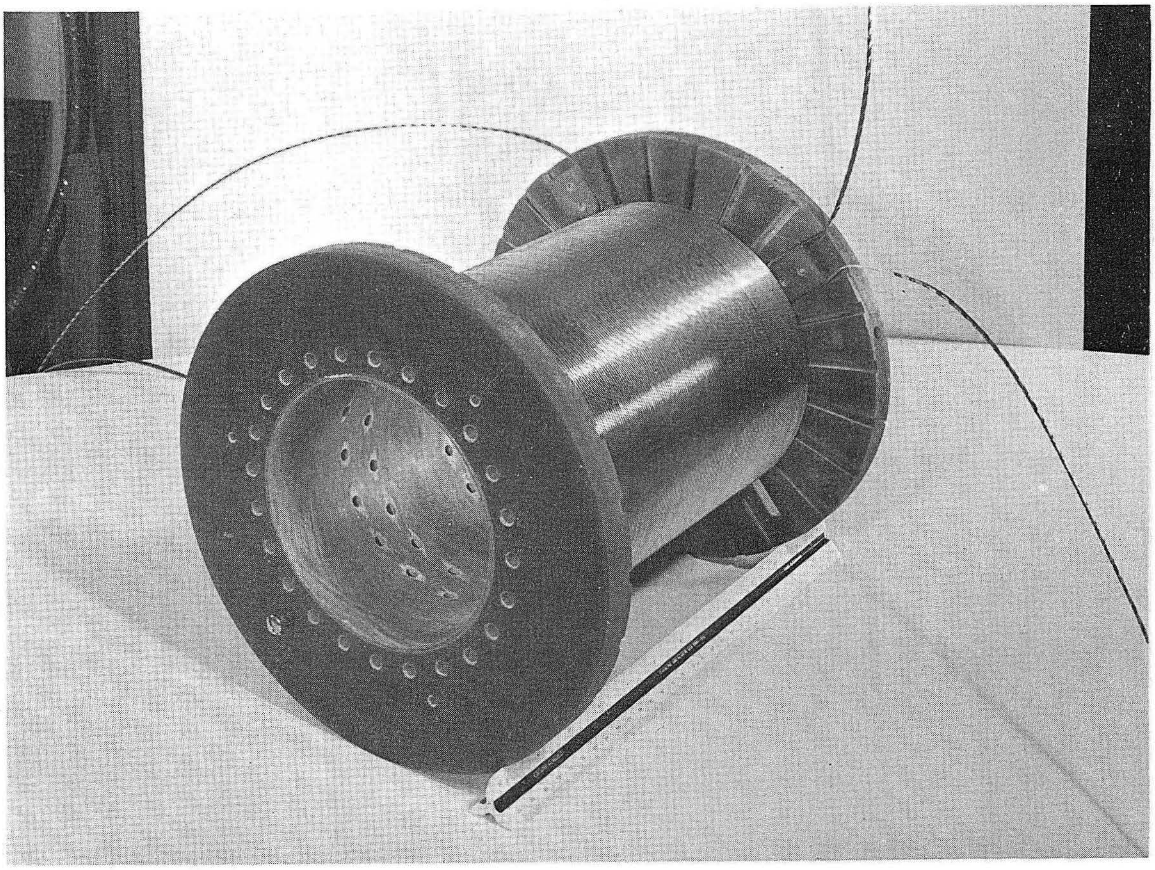
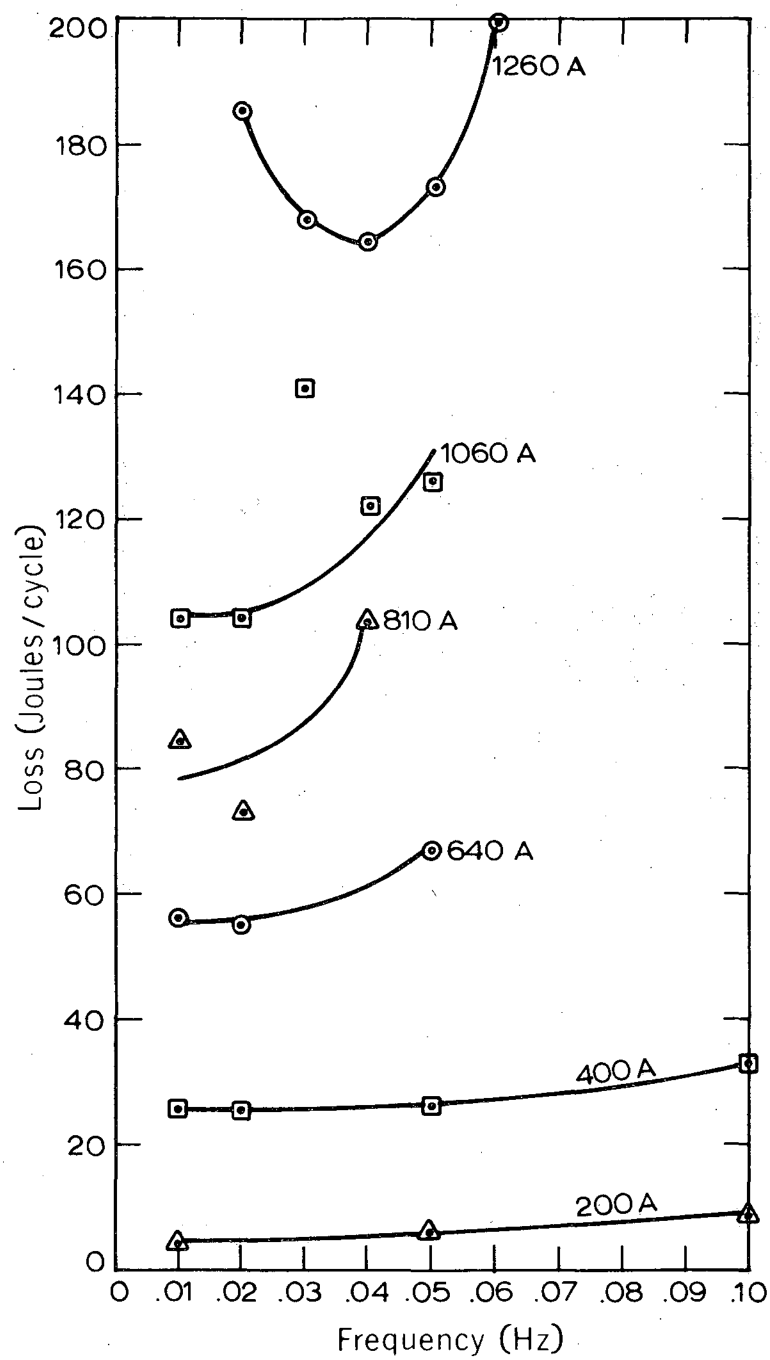

1000
8
6
4
2
100
8
6
4
2
10
8
6
4
2
1
All conductors .030" O.D.
Cu: S.C. = 3:1
Multicore-Untwisted
131 strands each
.0013"Diameter
"Airco"
Single strand
core .015"Dia.
"Supercon"
Multicore-Twisted
1.5 twist/inch
"Airco"
100 Amps ≈ 55 kG
Loss (Joules/cycle)
10
2
4
6
8
100
300
I max (Amperes)
XBL699 4888

Fig. 3



CBB 697-4719

Fig. 4



XBL 699 4889

Fig. 5

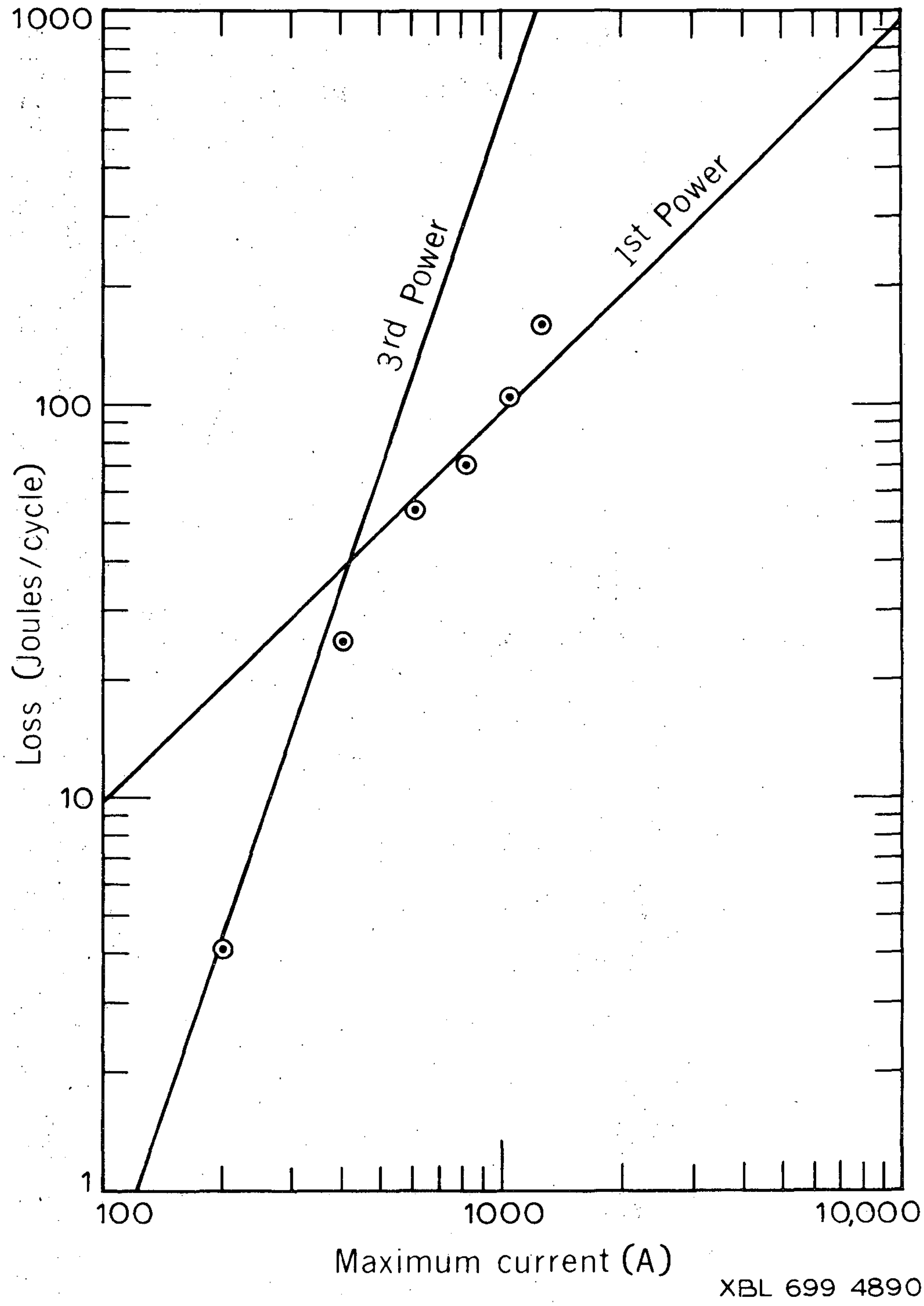
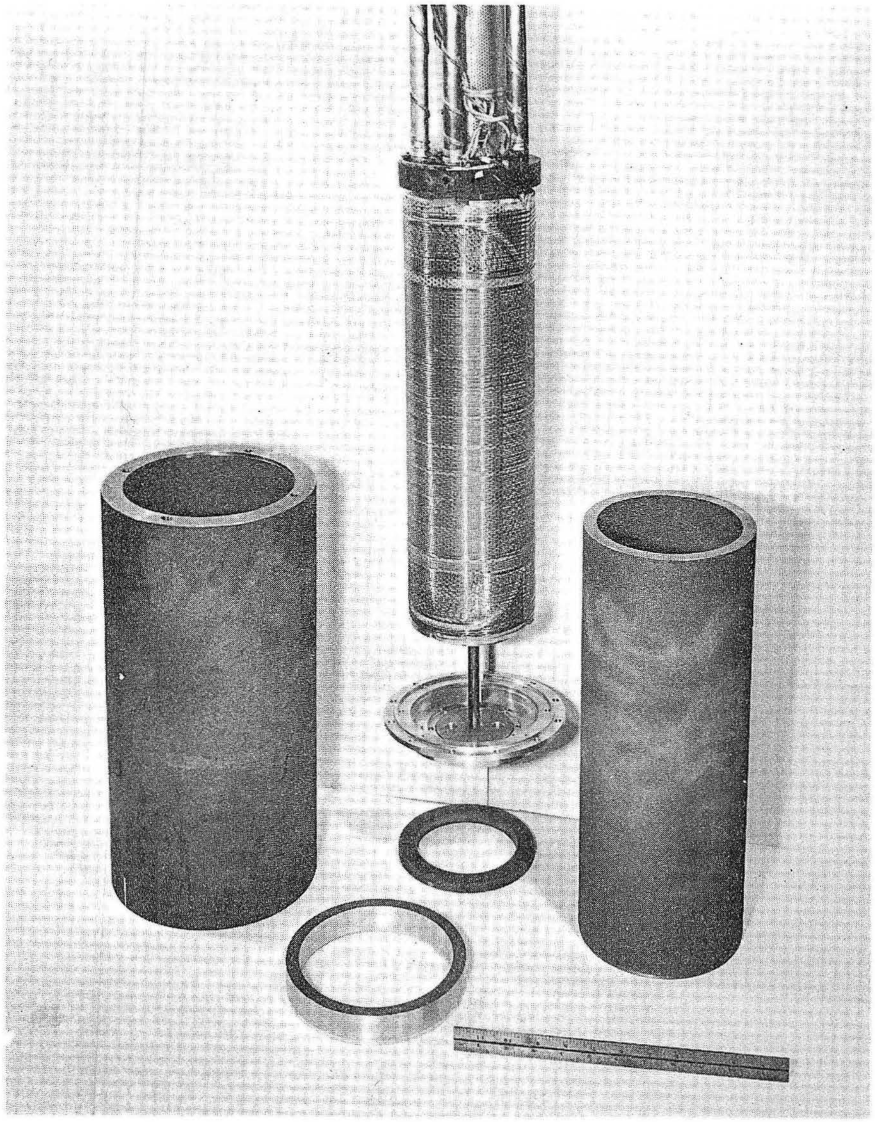
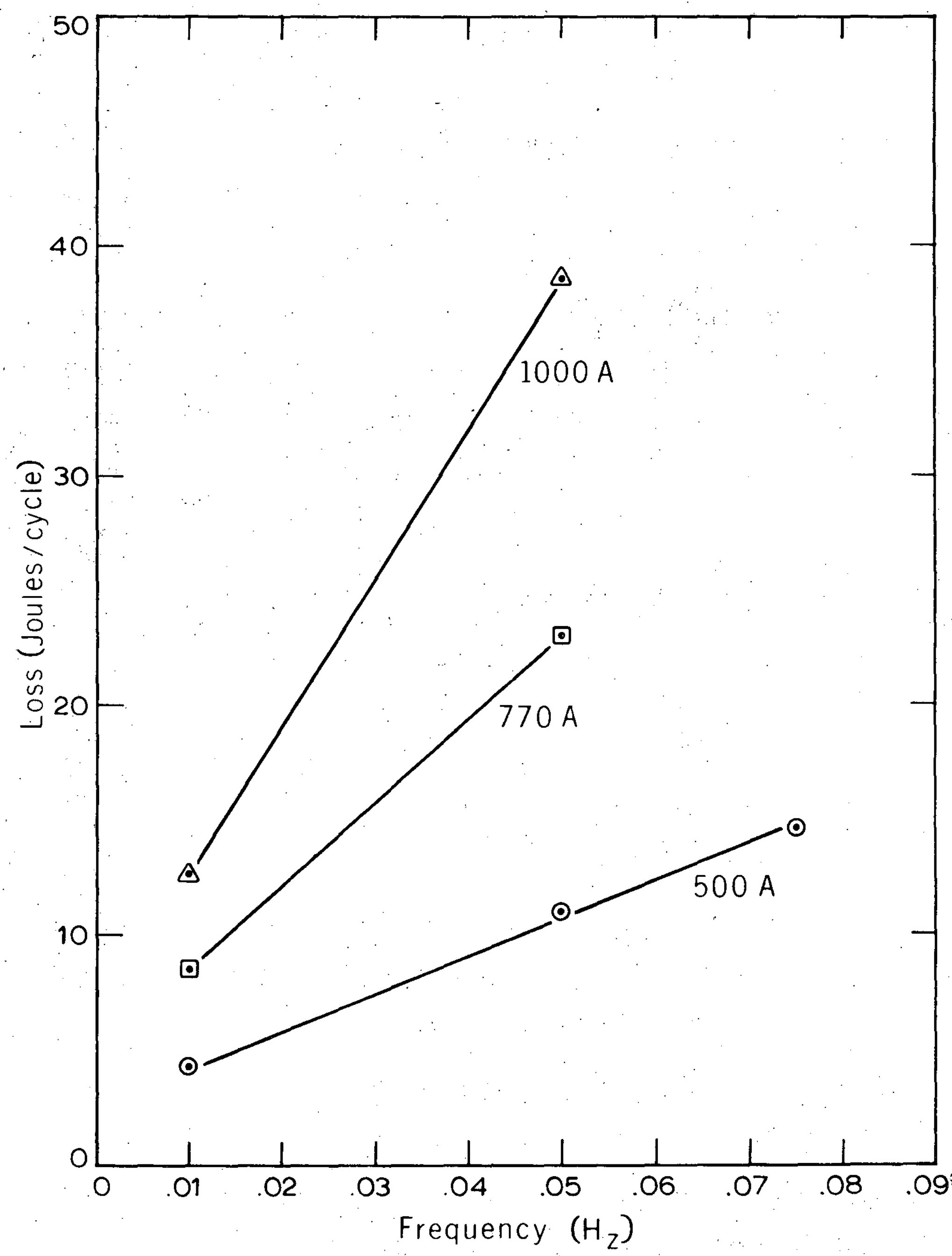

1000
100
10
1
Loss (Joules/cycle)
3rd Power
1st Power
100
1000
10,000
Maximum current (A)
XBL 699 4890

Fig. 6



CBB 697-4757

Fig. 7



XBL 699 4891

Fig. 8

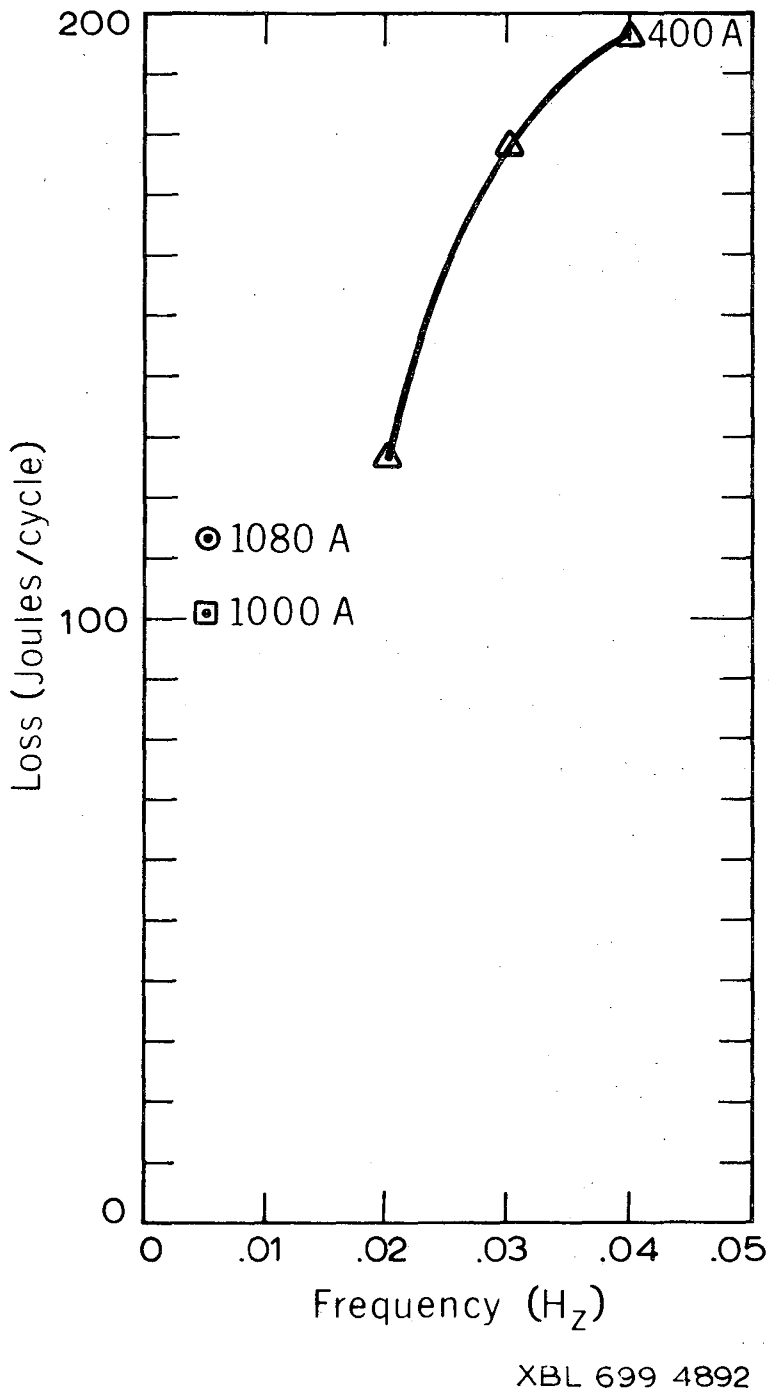
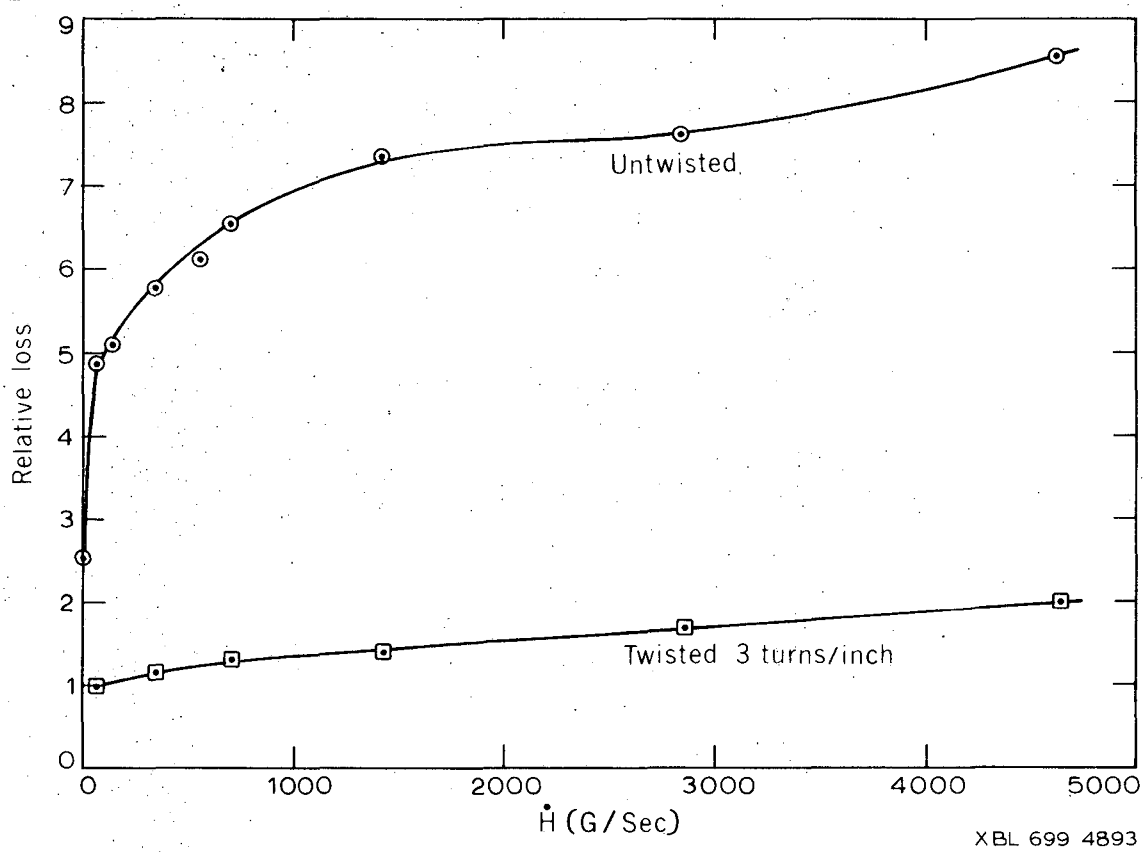
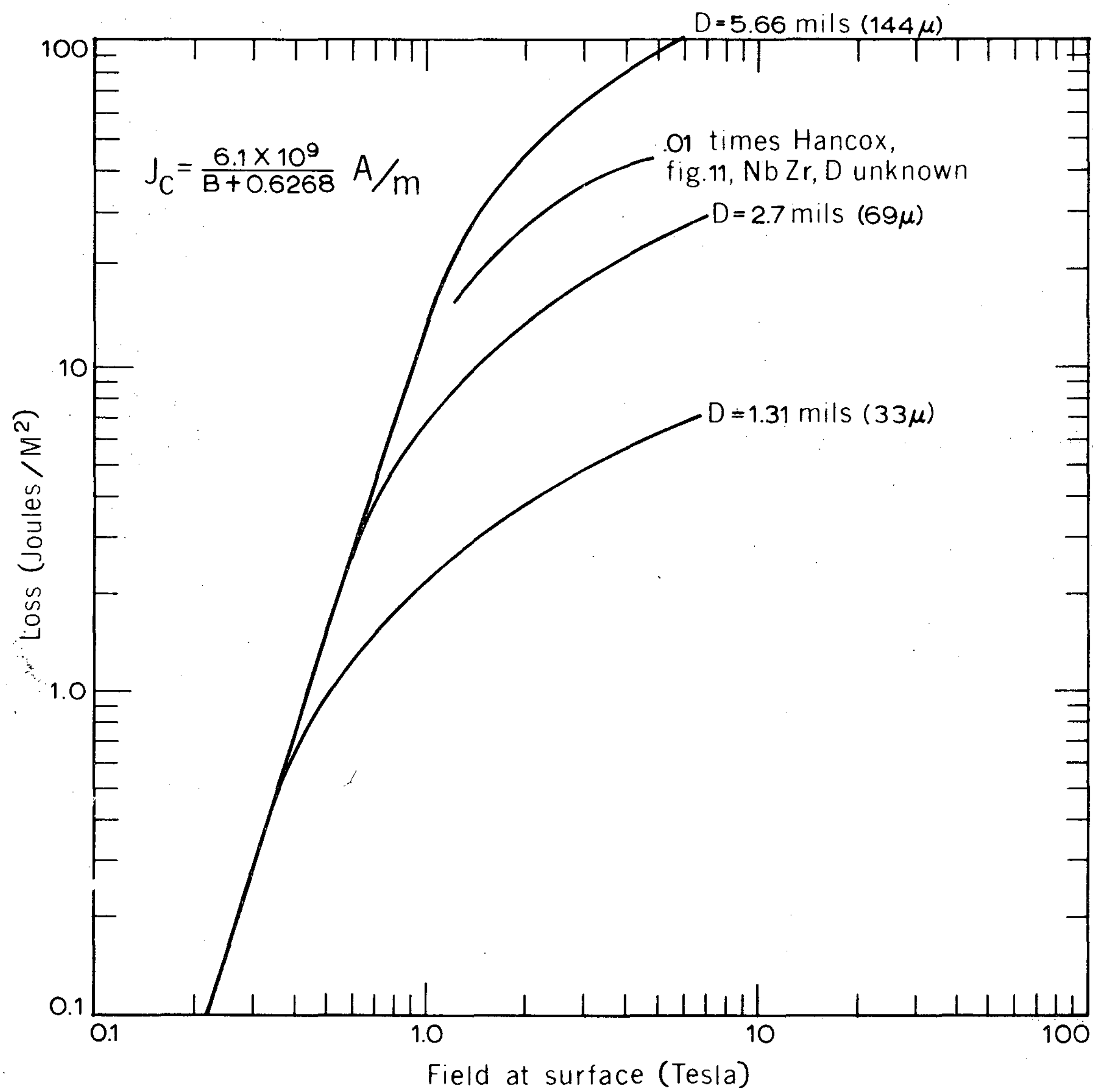

200
400 A
1080 A
1000 A
100
0
Loss (Joules/cycle)
0
.01
.02
.03
.04
.05
Frequency (Hz)
XBL 699 4892

Fig. 9



Relative loss
9
8
7
6
5
4
3
2
1
0
Untwisted
Twisted 3 turns/inch
0
1000
2000
3000
4000
5000
Ḣ (G/Sec)
XBL 699 4893

Fig. 10



XBL 699 4894

Fig. 11

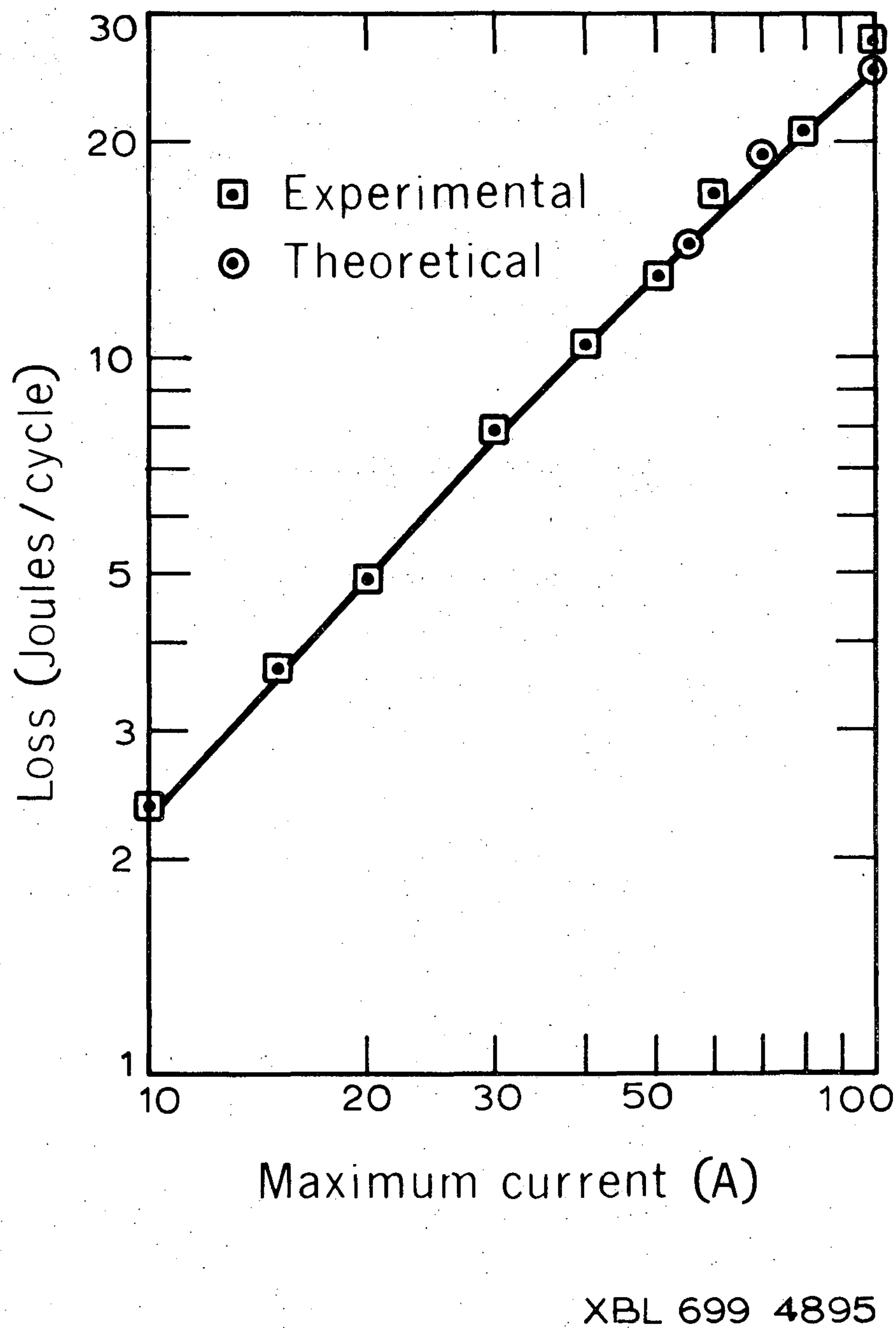

30
20
10
5
3
2
1
10
20
30
50
100
Loss (Joules/cycle)
Maximum current (A)
Experimental
Theoretical
XBL 699 4895

Fig. 12

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